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Bethesda, Md. 20084

INFRARED THERMOMETRY AND THE TELATEMP 44 AS A SHIP SYSTEM MAINTENANCE MONITORING TOOL

by

Barry L. Zimmerman

CENTRAL INSTRUMENTATION DEPARTMENT
DEPARTMENTAL REPORT

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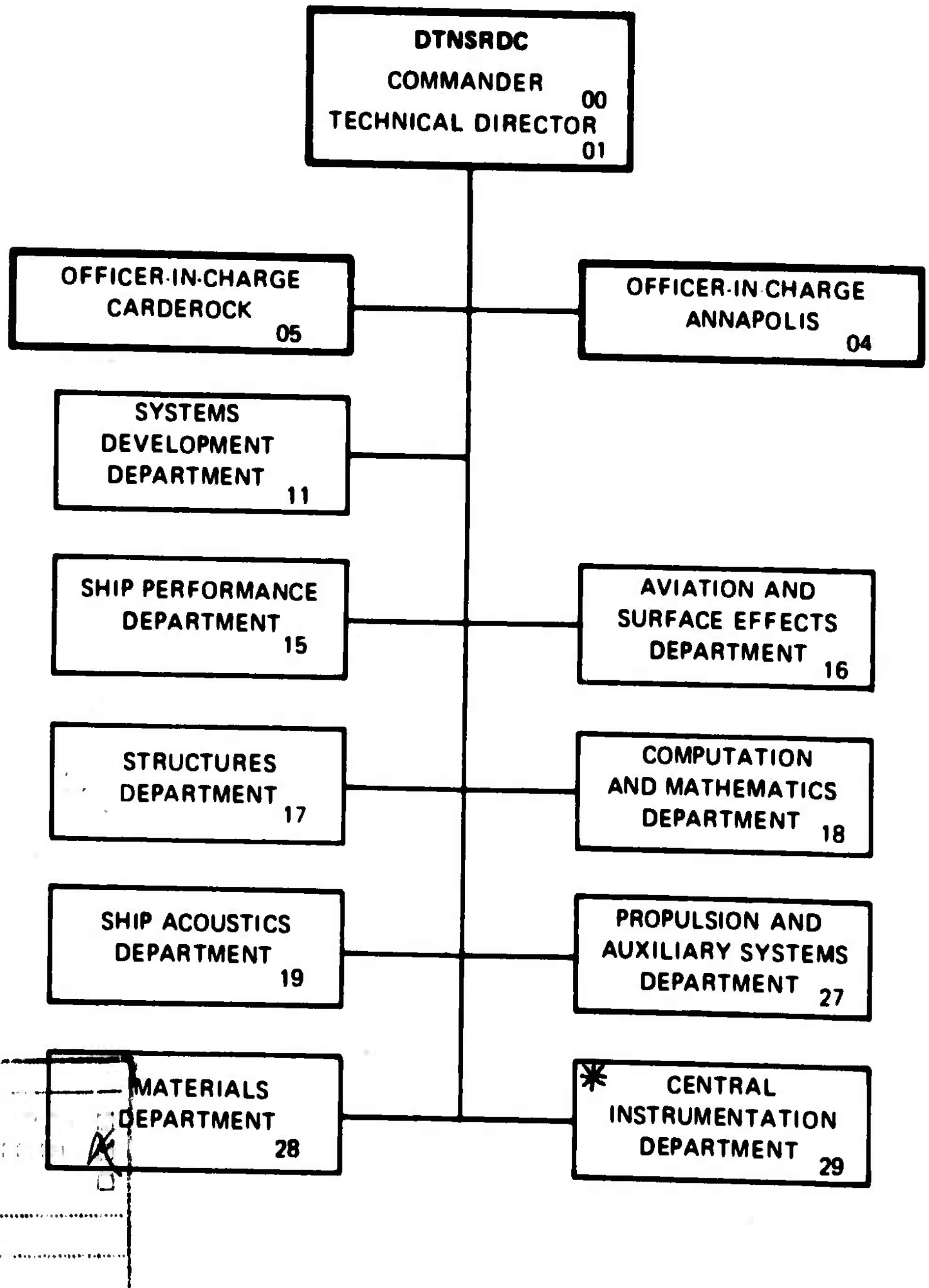

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Results of a laboratory investigation have demonstrated that infrared thermometry is a promising technique for measuring surface temperatures of Navy shipboard equipment and systems. Certain problems are encountered when applying the technique. These problems in general are discussed. A specific infrared device, the Telatemp Corp. Model 44, was evaluated. It substantially meets all its advertised specifications and with certain recommended modifications, should prove a valuable tool for shipboard thermometry.

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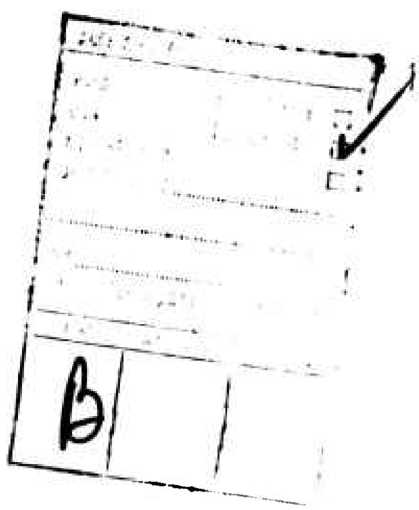


ABSTRACT

Results of a laboratory investigation have demonstrated that infrared thermometry is a promising technique for measuring surface temperatures of Navy shipboard equipment and systems. Certain problems are encountered when applying the technique. These problems in general are discussed. A specific infrared device, the Telatemp Corp. Model 44, was evaluated. It substantially meets all its advertised specifications and, with certain recommended modifications, should prove a valuable tool for shipboard thermometry.

INTRODUCTION

Monitoring selected system component operating characteristics can provide valuable information about the system's mechanical condition. Monitoring acoustic emissions, lubricating fluid contamination, vibration, flow rates, and temperature can tell much about structural integrity, bearing wear, pipe and heat exchanger fouling, and many other system conditions without actually tearing down the system.

Shipboard Maintenance Monitoring and Support (SMMS) site teams gather such information on-board Navy submarines to estimate the degradation of shipboard systems. Only systems which have exceeded established limits of degrdation require maintenance action. Eliminating systems known to be in good condition from maintenance schedules results in significant savings in overhaul cost and submarine downtime.

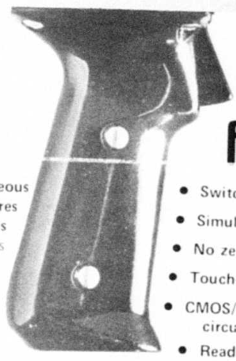
To accumulate this information inexpensively and reliably, quick, accurate, and easy to use measurement systems are needed. The SMMS site teams presently use intrusion type thermometers to measure fluid temperatures, and thermocouples to measure surface temperatures. Sensing elements are attached to an intermediate material which must be attached to take readings or the sensing elements are permanently attached and exposed to shipboard conditions. Accuracy and repeatability of measurements suffer. Numerous gauges must be periodically calibrated. Intrusion devices require separate fixtures installed at each measurement location. Thermocouples must be individually connected to readout instrumentation.

Infrared (IR) thermometry was proposed to gather the required temperature information and to make additional measurements where conventional techniques are impractical. IR thermometry promises to provide this temperature information at least as fast and accurately as intrusion devices or thermocouples without requiring permanent installation, costly fixtures, or time consuming attachment of sensors.

To test this proposal a commercial IR thermometer, the Telatemp Corp. Model 44 "Darringer", was purchased and evaluated for SMMS site team use.

the telatemp "darringer"

model 44



features

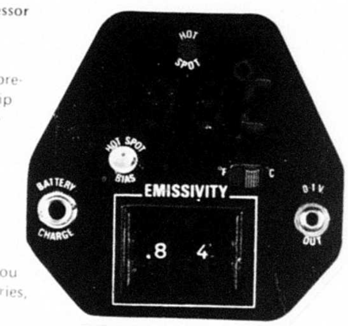
- Switch selectable Fahrenheit or Centigrade (0 to 1000°F or 0 to 600°C)
- Simultaneous digital readout and analog indication
- No zero controls (requires no calibration)
- Touch-sensitive On-Off hand-grip control
- CMOS/LSI digital processor circuitry
- Reading Hold

The "Darringer" Model 44 offers simultaneous analog indication and digital readout, requires no calibration and lets you scan target areas as fast as you want. Analog indication is provided by a "Hot Spot" indicator which brightens proportionately to target temperature. You can locate hot spots in seconds, and take accurate digital readings in either Fahrenheit or Centigrade.

Premeasurement calibration adjustment is unnecessary. An electronic chopper-stabilized preamplifier eliminates the need for "zeroing" controls. A unique solid-state On-Off hand-grip activates the instrument. Just pick up the "Darringer" and you're ready to make precise measurements, anywhere, any time.

The "Darringer" conquers emissivity adjustment. You enter compensation digitally with a 2-digit-thumbwheel. Adjustment accuracy is 1% (5 to 10 times better than a potentiometer). A compound Cassegrainian optical system shields the detector from harmful effects of direct target radiation and prevents inaccurate readings often caused by hot areas on the target periphery.

Four rechargeable Ni-Cad batteries provide the power (4 hours continuous). But when you don't need true portability, use AC line power, even while charging. Complete with batteries, you're holding a lightweight: under 2 pounds.



Control panel features .33" high LED display

applications

Scan areas quickly for hot spots • take measurements from a safe distance • measure temperatures of moving objects • reach inaccessible areas • pinpoint exact temperature regardless of target shape or surface

PERFECT FOR FAST SCANNING

The "Darringer's" eye for hot spots is quicker than the hand. And with the Peak-Reading Hold option, the hottest point in the scan is displayed on the large bright red LED readout. Pinpointing hot spots is easy. Open sights and the "Hot Spot" indicator combine to form an electro-optical bore sighting system that can't be beat. Focal distance can range from 8" to infinity.

The "Darringer" is all-new and incorporates the most advanced solid-state electronics available. The result: ±0.5% accuracy, exceptional reliability and long life, even in severe factory environments. A one-year parts and labor warranty is included in the selling price, along with a U.L.-approved battery charger, lockable carrying case and operating instructions.

telatemp corp
SURFACE THERMOMETRY
P.O. BOX 5160, FULLERTON, CALIFORNIA 92635
(714) 879-2901

Figure 1 Telatemp Model 44

The Telatemp 44 exhibits a reasonable balance between operating ease, accuracy, portability, ruggedness, and cost. It offers in one hand-held, battery-powered unit, a non-contact digital readout of surface temperatures between 0° and 600° Celsius or 0° and 1000° Fahrenheit (user selectable) with accuracies of $\pm 3^{\circ}C$ or $\pm 5^{\circ}F$. Temperatures are measured by simply pointing the instrument at the surface of interest (target) and reading the digital display. A "hot-spot" detector aids in the search for a region with abnormally high temperature. The unit is shipped with a "reading hold" feature which stores the last reading or optionally with a "peak reading hold" feature stores the highest reading attained while scanning a nonuniform surface. An emissivity adjust allows the instrument to be used with a widely varying surface characteristics. Figure 1 is the manufacturer's advertisement, showing the instrument and describing its features.

SECTION I - INFRARED THERMOMETRY AND THE TELATEMP 44

Infrared (IR) thermometers measure the temperature of a material by collecting energy radiated from the material's surface. A detector determines the radiant energy density (watts per square centimeter) emanating from the target area and converts this information to an equivalent surface temperature.

Planck's law gives the radiant energy emitted by a surface at a given wavelength λ for a band one micron (μ) wide. Planck's law may be written:

$$W_{\lambda} = 2\pi c^2 h/\lambda^5 (e^{hc/\lambda kT} - 1)$$

where

W_{λ} = spectral radiant emittance in $W/cm^2\mu$
c = speed of light, 2.99793×10^8 m/sec
h = Planck's constant, 6.6252×10^{-34} w=sec^2
λ = wavelength in microns
k = Boltzmann's constant, 1.38042×10^{-23} $\frac{\text{w-sec}}{\text{Kelvins}}$
T = absolute temperature in Kelvins

Substituting $\lambda = \frac{c}{\gamma}$ into Planck's law yields:

$$W\gamma = 2\pi h_{\gamma}{}^{5}/\frac{c^3}{(e^{k\gamma/kT-1})}$$

then substituting $x = \frac{h\gamma}{kT}$ yields:

$$W\gamma d\gamma = \frac{2\pi kT^4}{c^2h^3} (\frac{x^3dx}{e^x-1})$$

Figure 2 shows plots of this function for several values of T.

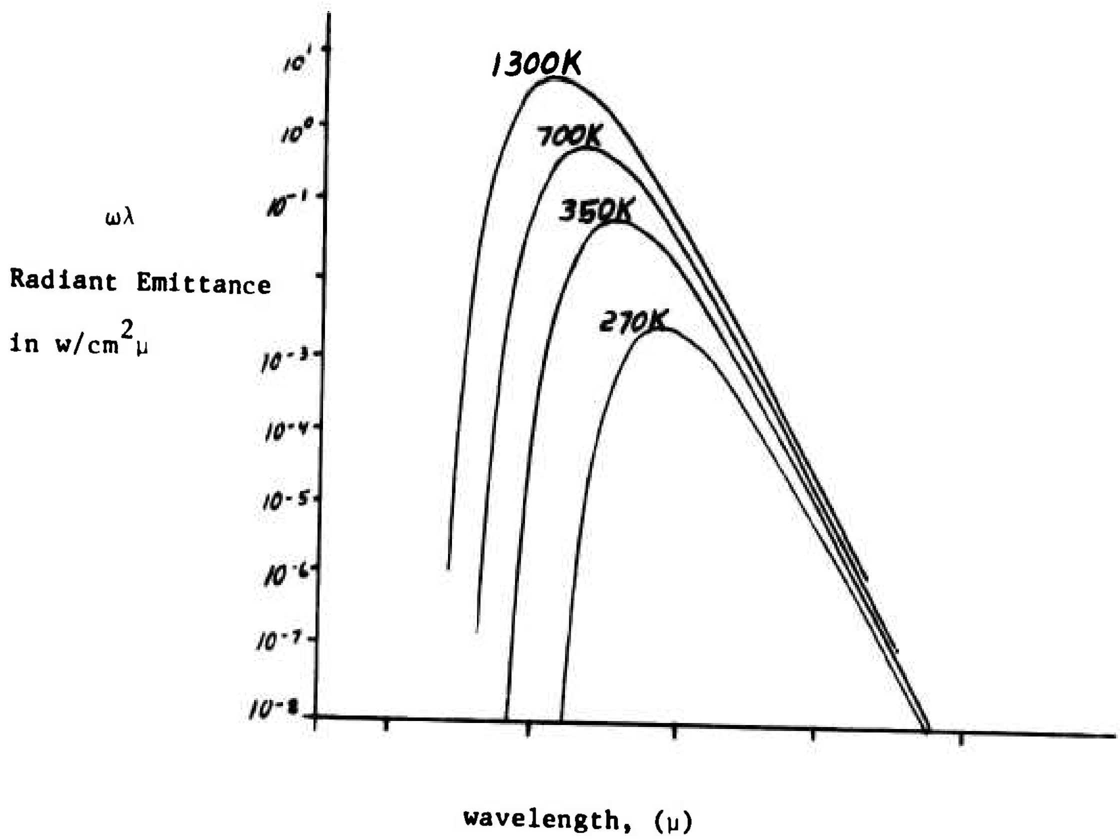


Figure 2. Radiant Emittance Versus Wavelength

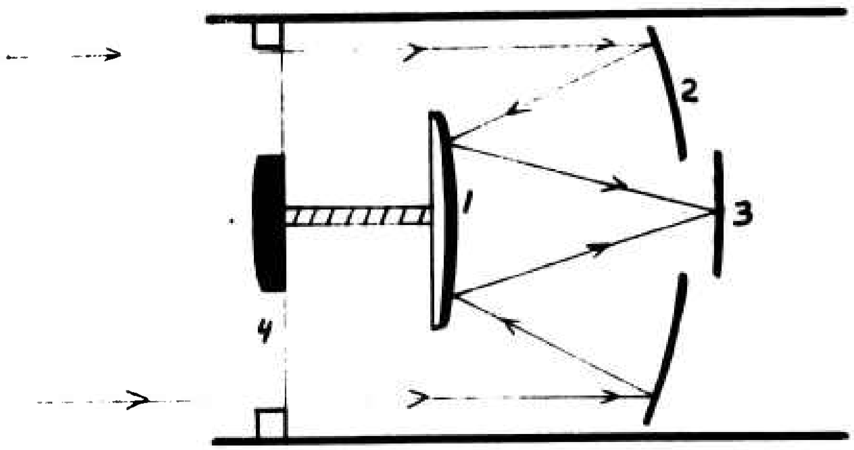
The radiant energy density is equal to the area under the curve, found by integrating the Planck expression over all wavelengths, and is given by the Stefan-Boltzmann Law:

$$W = e\sigma T^4$$

where

- W = radiant emittance in W/cm^2
- σ = the Stefan-Boltzmann constant, 5.67×10^{-12} W/cm^2K^4
- T = temperature in Kelvins ($K = {}^oC + 273^o$)
- e = surface emissivity

The Telatemp 44 uses Cassegrainian optics to focus radiated energy onto the detector. Figure 3 diagrams the optics placement in the Cassegrainian system. The primary mirror is concave; the secondary mirror is convex. This arrangement results in a smaller obscuration ratio* than a Newtonian System and a shorter length than a Gregorian system. Baffling (or hiding) of the detector from off-axis radiation is provided by the instrument's case and its' rather large secondary mirror.



1. Secondary Mirror
2. Primary Missor
3. Detector
4. Polypropylene

Figure 3. Cassegrainian Objective

The optical system is protected from dust and other foreign material by a thin sheet of polypropylene. Polypropylene has reasonably good transmission properties over the 2 to 15 micron operating range of the instrument. Figure 4 gives the approximate spectral transmission of the polypropylene sheet.

*The obscuration ratio is the ratio of the area of the secondary mirror to the area of the aperature formed by the case.

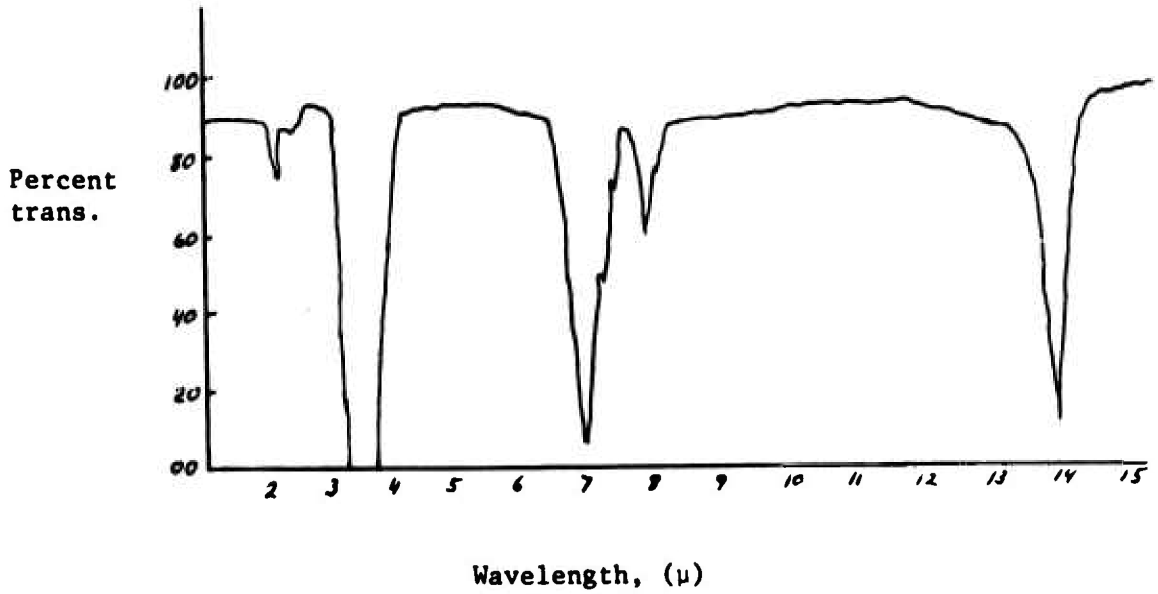


Figure 4. Spectral Transmission of Polypropylene

The energy collected by the optics is focused on a Bismuth-Antimony detector whose sensitivity is shown in Figure 5.

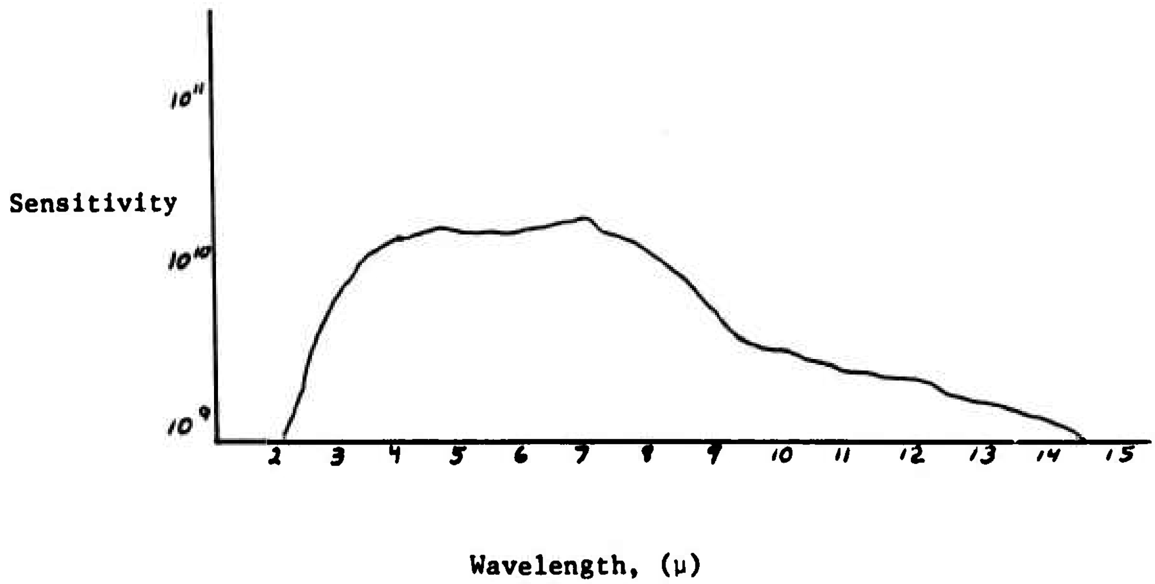


Figure 5. Spectral Sensitivity of Bi-S_b Detector

If the detector response and the polypropylene transmission were constant for all wavelengths, the detector's output could be calculated from the Stefan-Boltzmann Law, $W = k_1 \sigma T^4$. Here k_1 is a product of the emissivity of the surface, the relative transmissivity of the polypropylene, and the detectivity (sensitivity) of the detector. However, the true radiant energy spectrum is altered not by a constant but by the detector's bandwidth limitation and the polypropylene's absorption bands. Thus the radiated energy spectrum must be multiplied by the spectral sensitivity of the detector ($D\lambda$) and the spectral transmittance of polypropylene (T_λ) to determine the energy spectrum referenced to the detector output. The energy density curves of Figure 2 are severely altered by these two factors. Yet, since the curves are altered similarly, the detector's output is still very nearly proportional to the fourth power of T.

The detector's output is applied to an operational amplifier. A second signal is applied to the operational amplifier to compensate for the temperature sensitivity of the detector itself. This makes it possible for the Telatemp 44 to operate over a wide range of ambient temperatures. A nonlinear diode array shapes the amplifier's gain curve to approximate the $1/T^4$ response necessary to counter the fourth power detector output. Other biases and gain controls correct for target emissivity and scaling between Celsius and Fahrenheit readouts.

A sample and hold amplifier retains a particular reading when using the "reading hold" or optional "peak-reading hold" features.

An analog-to-digital converter converts the scaled analog signals to the digital information presented on the light-emitting-diode (LED) displays. A zero in the hundreds digit is blanked.

A feature called a "hot-spot" detector uses an LED as an indicator. The current through this diode represents the differential between the target temperature and an adjustable reference. Indicator illumination is proportional to the diode current.

The Telatemp 44 is turned on when the thermometer is picked up by its pistol grip handle, and readings are taken by aiming along the case at the desired target.

SECTION II - LABORATORY EVALUATION

The Telatemp 44 was evaluated in the laboratory to check for conformity to the manufacturer's advertised specifications and to determine the actual characteristics of this specific sample (serial #47).

TABLE 1 TELATEMP MODEL 44 SPECIFICATIONS

TELATEMP INFRARED THERMOMETER

MODEL 44

SPECIFICATIONS

Scale Range	0 to 1000°F or 0 to 600°C, switch selectable
Accuracy	±0.5% of F.S.
Repeatability	±0.5% of F.S.
Resolution	±0.2% of F.S.
Noise	N.E.T. (effective noise temperature) ≤ 1.0°C
Linearity	±0.5% F.S.
Zero Drift Control	Automatic
Target Spot Size	≤ D/20 at instrument's focal plane. (Example: 1½" @ 30")
Response Time	< 50 mS for "Hot-Spot" indicator, < 1.0 S for digital read-out
Focal Distance (factory adj.)	8" to infinity (30" standard)
Spectral Response	2 to 15 microns, wideband
Emissivity Adjustment	$0.1 \leq \varepsilon \leq 1.0$
Environment	Non-operating: 0 to 150°F, Operating: 35 to 120°F
Electro-Optical "Bore Sighting"	Open sights define target area in conjunction with "Hot Spot" indicator
Outputs	0 to 1.0V DC linearized output is provided
Power Source	Rechargeable Ni-Cad batteries for more than 4 hours continuous operation from overnight charge. Operable from AC line power and while charging.
Low battery Indication	Period after "F" or "C" on display indicates charge is necessary
Bias Control	Adjusts threshold value of "Hot Spot"

TABLE 1 TELATEMP MODEL 44 SPECIFICATIONS cont'd

TELATEMP INFRARED THERMOMETER

MODEL 44

SPECIFICATIONS

On-Off Control	Touch-sensitive electronic switch built into hand-grip
Reading Hold	Holds readout while trigger switch is depressed
Tripod Mounting	Built into hand-grip (furnished with "On" switch clip)
Accessories Provided	U.L. approved battery charger, 120/240V, 50-60 Hz, 8W; Cycolac case with Ethafoam protective cushioning, lock and key, carrying handle; operating instructions and table of surface emissivity values
Accessories Available	Peak Reading Hold, Wrist Strap

II.A. CALIBRATIONS TESTS

II.A.1. Scale Range

The Telatemp 44 displays measured temperatures with 3/8 inch high red (LED) numerals. The three decade display can show 00 to 999. The display is updated every 2/3 second. Actual calibrated scale ranges are 0° to 999°F or 0° to 600°C.

Above 600°C the display continues to increase up to 999. Above 999, either °C or °F, the display continues to show readings less the most significant digit. For example, 1055 is displayed as 55. A calibration to determine accuracy and an upper limit may allow an operator to exceed the specified range of the device.

By similar interpretation, measurements below 0°C or 0°F can be made. The data in Table 2 records the Telatemp 44's extended low temperature performance. In this set of data, as with all displayed temperatures, zeros in the hundreds digit are blanked.

The target temperature was measured with a thermocouple installed in the steel block which served as the target in this test. The thermocouple was calibrated in an oil bath with a glass thermometer which was calibrated at the National Bureau of Standards (NBS). The oil used was a commercial grade brake fluid.

TABLE 2 - EXTENDED LOW TEMPERATURE PERFORMANCE

Target Temperature °C	Target Temperature °F	°C Telatemp Reading	°C Interpreted Reading	°F Telatemp Reading	°F Interpreted Reading
-40	-40.0	60	-40	60	-40
-36	-32.8	64	-36	66	-34
-32	-25.6	68	-32	73	-27
-23	-9.6	77	-23	91	-09
-11	+14.0	89	-11	12	12
-8	+17.6	91	-9	16	16
-7	+19.4	92	-8	18	18
-6	+21.2	93	-7	20	20
-5	+23.0	95	-5	22	22
-4	+24.8	96	-4	24	24
-3	+26.6	97	-3	26	26
-2	+28.4	98	-2	28	28
-1	+30.2	99	-1	29.5	29.5
0	+32.0	00	0	31	31

Table 2 demonstrates that temperature measurements as low as -40 degrees on either Celsius or Fahrenheit scales can be obtained simply by subtracting 100° from the reading. Though SMMS teams make no measurements in this temperature range, these results lend more confidence to readings at the lower end of the specified operating range.

II.A.2. ACCURACY

Precise calibration of the Telatemp 44 proved to be more difficult than anticipated. Attempts to locate a calibration source capable of reaching the Telatemp 44's full scale of 600°C (1000°F) were unsuccessful. Since the cost to purchase such a unit was prohibitive and since few applications were expected above 260°C (500°F), calibration efforts were concentrated in the lower half of the advertised range.

A number of tests were performed using different calibration sources, attempting to find one with sufficient accuracy range, and known emissivity. Also, it was necessary to find a source which could be used in the field. On-site calibration would be required for IR thermometers used on-board ships. Drift and errors due to component aging and optics contamination are unavoidable, therefore periodic calibration checks should be made even though the manufacturer states that "premeasurement calibration adjustment is unnecessary."

The first calibration was performed using a Barnes Engineering large-area blackbody. Although the blackbody was equipped with a good temperature controller, a Barnes Engineering PRT-5 Precision Radiation Thermometer was used as a separate reference. Specified accuracy for the Barnes PRT-5 is ±0.5°C.

Advertised emissivity (see Section III.A. for definition) for the blackbody was .97 ±.03. A Telatemp 44 emissivity setting of .97 was used. Celsius and Fahrenheit readings were taken at this setting. In addition, secondary Celsius readings were taken at emissivity settings of .50 and .20. The purpose of this secondary data was to uncover any peculiarities which might require further investigation. No further use of this secondary data was made.

All Telatemp 44 readings were read from its digital display, interpolated to half degrees when the display's least significant digit (one degree) alternated between two consecutive numbers.

Table 3 is a copy of the tabulated results and Figure 6 is a plot of the Barnes PRT-5 readings versus the Telatemp 44 readings.

A typical plot of calibration data, such as Figure 6, consists of two graphs. First, a plot of Telatemp 44 readings versus the source temperature; and second, a plot of the deviation of the Telatemp 44 readings in degrees Celsius from the computed best-straight-line. Ideally all the data will fall exactly on a straight-line of slope 1.000 passing

TABLE 3 - CALIBRATION WITH BARNES PRT-5

Control Setting	Barnes PRT-5	e = .97	Telatemp e = .5	e = .2	Telatemp e = .97
°C	°C	°C	°C	°C	°F
50	50	53	79	137	128
55	55.5	58.5	89	149	137
60	60	63	95	159	145
65	64.5	67	101	168	153
70	70	72	108	179	162
75	74.5	77	115	190	171
80	80	83.5	122.5	203	182
85	84	88	129	212.5	191
89	88.5	94	139	226	201
95	94	99	143.5	234	210
100	99	104	151	245	218
105	103.5	109.5	158	256	229
110	108.5	114	166	265	238
115	114	119	173	275	246
120	119	124	180	285	255
125	124.5	129.5	188	295.5	265
130	130	135	195	305	274
135	135	140	202	315.5	284
140	139.5	145	211	326	293
145	144.5	149.5	217	335	301
150	149	155	224	346	311
155	154	160	230	356	320
160	159.5	165.5	237	367	331
165	164	170	245	377	339
170	169	175	251.5	388	348
175	174	180	258	396	357
180	179.5	185.5	264	406	366
185	184.5	191	270	415	375
190	189.5	196	276	425	385
195	195.5	202	283	435	396
200	201	208	289	444	406
205	205	213	297	455	416
210	210.5	217.5	304	464	424
215	215	223	311	474	434
220	220.5	228	318	481	443

X	Y
50.00	53.00
55.50	58.50
60.00	63.00
64.50	67.00
70.00	72.00
74.50	77.00
80.00	83.50
84.00	88.00
88.50	94.00
94.00	99.00
99.00	104.00
103.50	109.50
108.50	114.00
114.00	119.00
119.00	124.00
124.50	129.50
130.00	135.00
135.00	140.00
139.50	145.00
144.50	149.50
149.00	155.00
154.00	160.00
159.50	165.50
164.00	170.00
169.00	175.00
174.00	180.00
179.50	185.50
184.50	191.00
189.50	196.00
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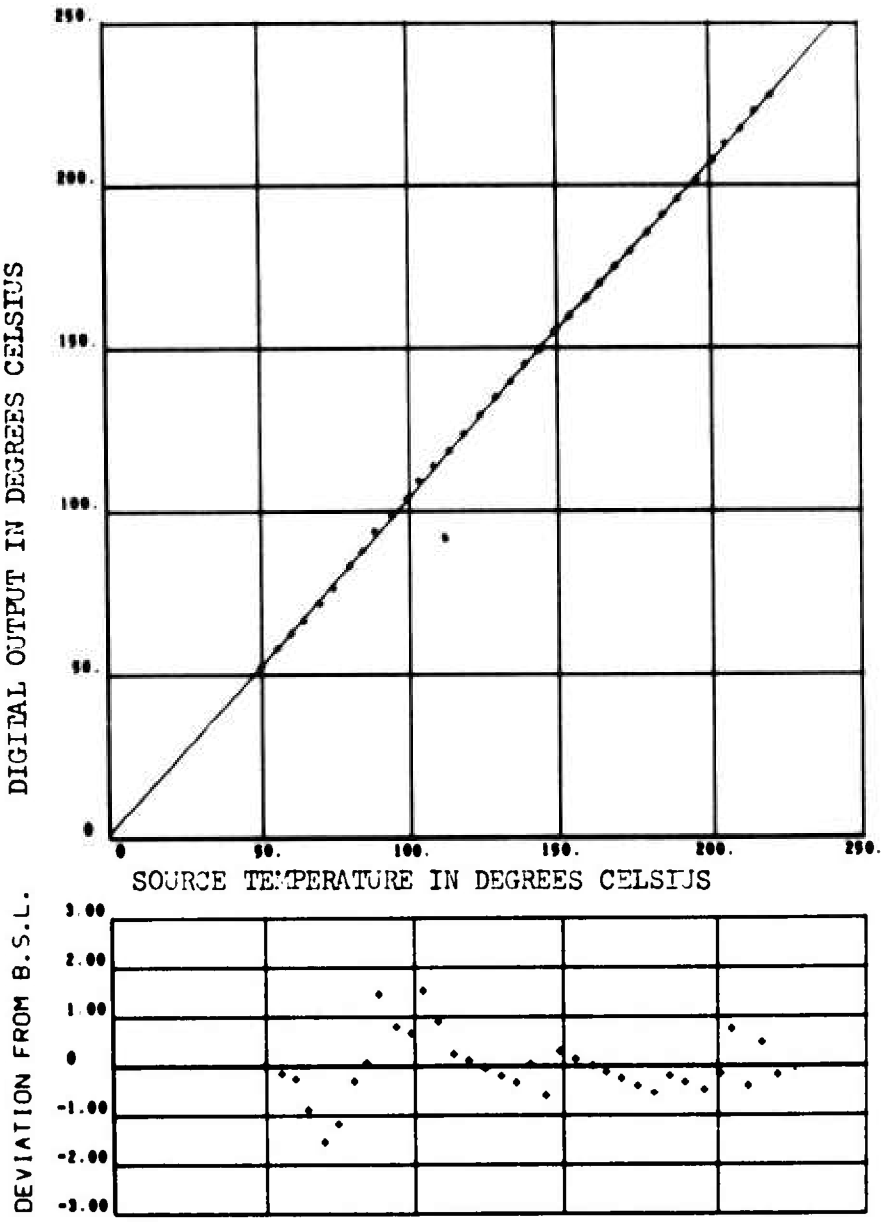
210.50	217.50
215.00	223.00
220.50	228.00



BEST STRAIGHT LINE IS Y = 1.0275 X + 1.5840
MAXIMIM DEVIATION FROM B.S.L. IS 1.5684 DEG C.
RMS ERROR OF B.S.L. FIT IS .6245 DEG C.

Figure 6. Digital Calibration with Barnes PRT-5

through 0. This would represent the ideal transfer characteristic between the standard source temperature and the temperature displayed by the Telatemp 44. However, the combination of measurement and Telatemp 44 errors results in a scatter diagram.

The transfer characteristics are evaluated by a best-straight-line technique. The best-straight-line can show any average offset (the y-intercept), any gain error (the slope), and any nonlinearity (the deviations of individual data points from the best-straight-line).

The best-straight-line has the equation

$$y = b + mx$$

For a set of N data points, intercept b and slope m are found by simultaneously solving the equations

$$\begin{cases} \sum_{j=1}^{N} y = bN + m \sum_{j=1}^{N} x \\ \sum_{j=1}^{N} xy = b \sum_{j=1}^{N} x + m \sum_{j=1}^{N} x^2 \end{cases}$$

which yields:

$$b = \frac{\Sigma y \, \Sigma x^2 - (\Sigma x)(\Sigma xy)}{N\Sigma x^2 - (\Sigma x)^2}$$

$$m = \frac{N\Sigma xy - (\Sigma x)(\Sigma y)}{N\Sigma x^2 - (\Sigma x)^2}$$

The deviation from the best-straight-line is found by solving

$$dev_j = y_j - b - mx_j$$

Values obtained by solving this equation are used to generate the lower curve. The upper curve is simply the plotted data with the best-straight-line superimposed.

From the calculated values of deviation from best-straight-line, a maximum value is determined. This value represents the maximum measurement error if the gain is unity and the offset is zero.

The RMS error of the best-straight-line is

$$\sqrt{\Sigma \, dev_j^2}$$

It represents all of the data point deviations, not just the maximum.

Figure 6 then indicates a gain which is 2.75% high if the target emissivity was exactly .97. From subsequent calibrations it is believed that the apparent gain error was a combination of both a Telatemp 44 gain error and a target emissivity greater than .97.

Figure 6 indicates an average offset error of 1.5840°C. It also indicates that the peak nonlinearity is 1.5684°C. In Barnes PRT-5 data plotted in Figure 6 the deviation from best-straight-line of 1.5684°C is within the Telatemp 44 specifications, but the offset error causes readings to be out of specification.

Confidence in these readings is low because there was no record of a recent calibration of the Barnes PRT-5 from a reliable standard. This particular calibration, however, was valuable in two respects. First, it showed a pattern of deviation from best-straight-line which was to be repeated in later calibrations.

Second, it showed that the Fahrenheit readings taken agree to within ±1.2°F with the value which would have been obtained by converting the Celsius readings to Fahrenheit values by the equation:

$$^{o}F = \frac{9}{5}(^{o}C) + 32^{o}$$

Subsequent conversion checks have shown that at least ±.5°F of this error is due to analog to digital conversions.

The second calibration was performed at the National Bureau of Standards. The Telatemp 44 was suspended above a stirred oil bath and aimed at the oil surface. The Telatemp 44 analog output was monitored on a digital voltmeter giving reading resolution of ±0.1°C. The calibration was run over a range of 100°C to 270°C (212° to 518°F). Violent smoking of the oil bath and inconsistent readings above 200°C (392°F) invalidate these readings.

Each reading in Table 4 is the average of three readings taken at each bath temperature. Where there are first and second readings given, six readings were taken in two groups of three readings.

The data up to 200°C from Table 4 are plotted in Figure 7. The plot shows a positive peak deviation at about 100°C (212°F) and a negative peak deviation at about 130°C (266°F). Similar peaks appeared on the Barnes test, Figure 6. Differences in display resolutions account for the relative smoothness of Figure 7, compared with Figure 6.

TABLE 4 CALIBRATION WITH NBS OIL BATH

U.S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS
WASHINGTON, D.C. 20234

REPORT OF TEST

INFRARED THERMOMETER
Serial Number 47

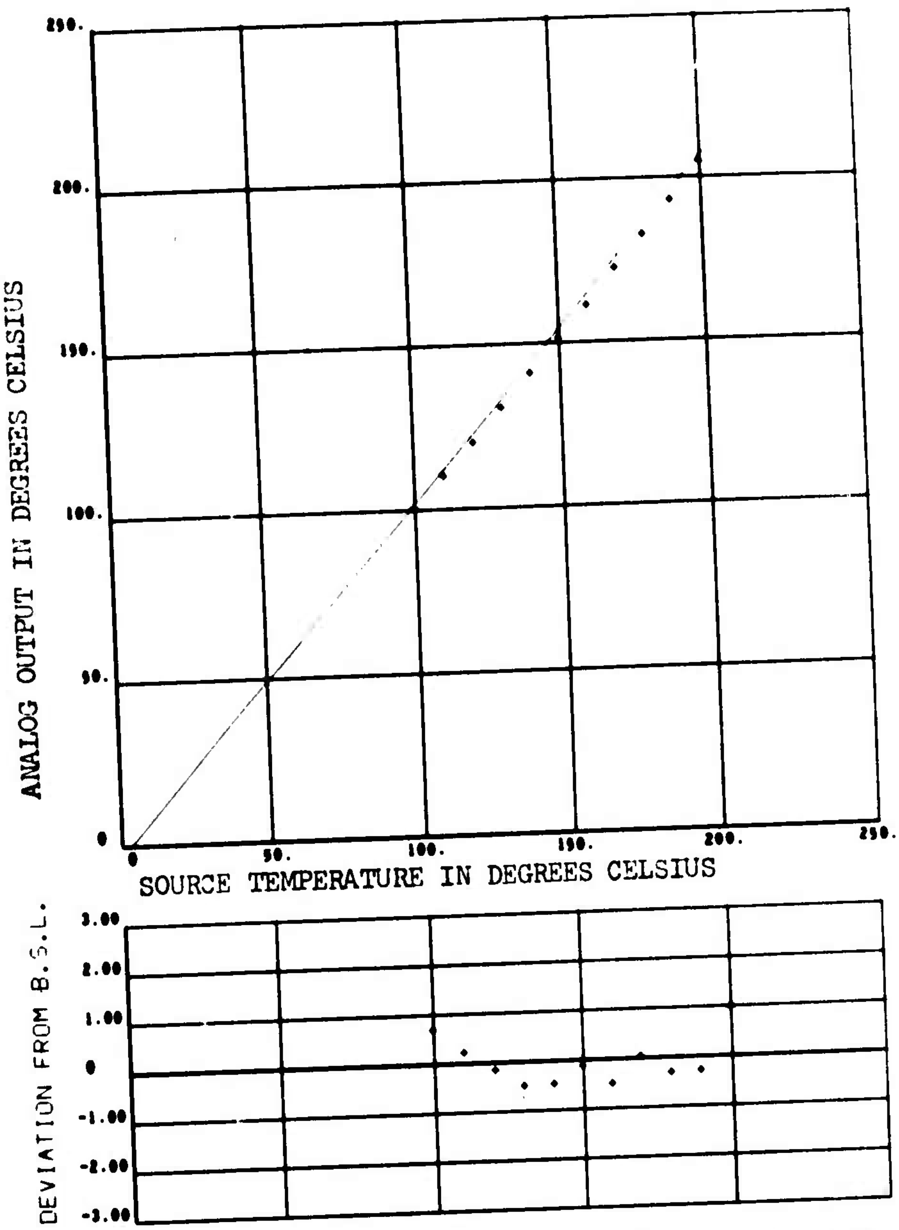
Submittted by

Department of the Navy
Naval Ship Research and Development Center
Bethesda, Maryland

The infrared thermometer was calibrated by intercomparison with a standard platinum resistance thermometer in stirred liquid baths at 21 temperatures. The results obtained are given below:

Bath Temperature °C	Average Reading of Infrared Thermometer °C First Reading	Second Reading
99.99	100.7	
109.99	110.6	
120.01	120.6	
130.00	130.6	
139.99	141.0	
150.00	151.7	
160.00	161.7	
170.01	172.6	
179.99	182.6	
190.01	193.0	
200.01	204.9	
199.98	204.5	
199.98	204.3	
210.00	212.7	213.0
219.97	222.9	222.7
230.01	232.0	232.1
240.00	243.3	243.3
250.00	254.7	254.2
259.97	263.4	263.1
260.00	263.6	
270.00	271.8	

99.99	100.70
109.99	110.60
120.01	120.60
130.00	130.60
139.99	141.00
150.00	151.70
160.00	161.70
170.01	172.60
179.99	182.60
190.01	193.00
199.99	204.60



BEST STRAIGHT LINE IS Y = 1.0361 X - 3.6272
MAXIMIM DEVIATION FROM B.S.L. IS 1.0109 DEG C.
RMS ERROR OF B.S.L. FIT IS .4653 DEG C.

Figure 7. Analog Calibration with NBS Oil Bath

No gain information can be deduced from this calibration since the emissivity of the oil surface was not known. Over the range of plotted data, stirring was sufficient so that the surface of the bath represented the bath temperature.

The third calibration was actually a series of experiments run at the David Taylor Naval Ship Research and Development Center (DTNSRDC) to evaluate the possibility of developing a calibration standard using a stirred oil bath to heat a metal surface coated with a known emissivity paint.

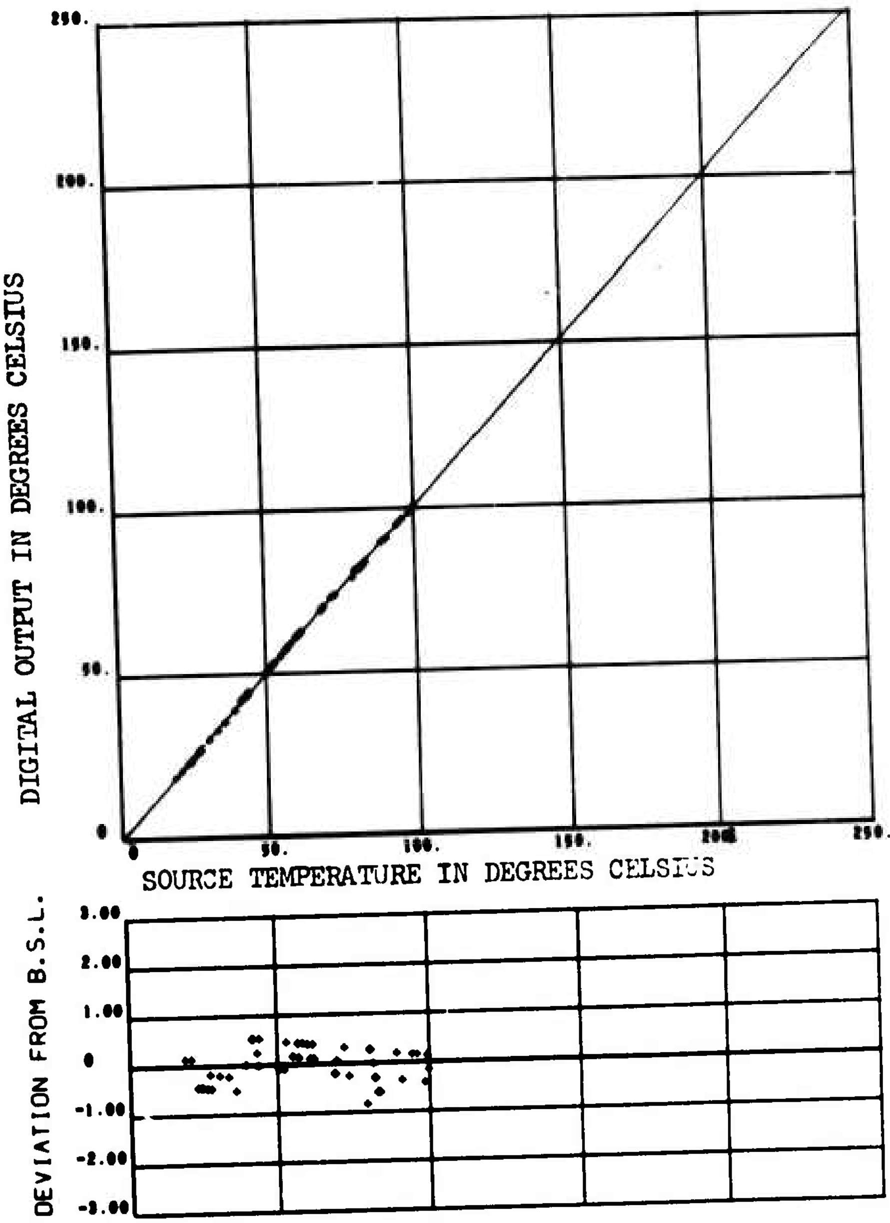
The target for the Telatemp 44 thermometer was a 3½ inch diameter film can lid painted with Krylon "ultra-flat-black" paint having a measured emissivity of .93. The Telatemp 44 emissivity control was set to this value. The value of .93 represents the average emissivity the target displayed in emissivity sensitivity tests, and spot check of hot masses against thermocouple standards. The target was floated on an oil bath heated by a simply regulated heater. The bath was stirred prior to each reading until the reference thermometer, a liquid-in-glass thermometer calibrated at NBS, remained stable. Between the readings, the bath was loosely covered to prevent the loss of heat at the surface. Temperature readings were taken in ^{o}F but converted to $^{o}C = 5/9\ (^{o}F-32)$ for the plots of Figure 8 to keep consistent with other data.

Data were also taken to show the difference in temperature between the bath and the outside of the container. Two sets of these data are shown in Table 5. The first set was taken with mild stirring, smooth circulation of the oil in the container. A second set of data was taken with violent stirring, splashing. With violent stirring, the container temperature stayed within $1^{o}F$ ($.5^{o}C$) of the fluid whereas $5^{o}F$ ($3^{o}C$) errors existed in the mildly stirred bath. One reading taken with no stirring at all showed a fluid temperature of $176^{o}F$ ($80^{o}C$) and a container temperature of $124^{o}F$ ($51^{o}C$). All container temperatures were measured by aiming the Telatemp 44 at the container's blackened outer surface. Container emissivity was established at .93 on the basis of the $75^{o}F$ reading during the violent stirring test, and confirmed with a touch thermocouple.

These experiments proved valid the technique of using a stirred fluid to heat a thin metal sheet coated with known emissivity paint. A calibration standard using this technique and following a form proposed by Dr. Felix Schweizer of the Metrology Engineering Center, Pomona, CA., was then designed.

Two of these standards were built, differing in the size of the container and shape of the target. The first used a 5.8 litre container and the target was the flat bottom of the inside of a small beaker, painted with 0.93 emissivity paint. The second standard used an 8 litre container for more thermal mass and a sloped bottom target to increase the emissivity. Appendix A describes the design and construction of these calibration standards.

X	Y
19.17	19.17
21.11	21.11
23.33	22.78
24.44	23.89
25.00	24.44
26.67	26.11
27.50	27.22
27.78	27.22
30.83	30.56
33.61	33.33
36.11	35.56
39.44	39.44
41.67	42.22
42.22	42.78
43.61	43.89
43.89	43.89
44.44	45.00
51.11	51.11
51.11	51.11
52.78	52.78
53.33	53.89
55.56	55.83
57.22	57.78
57.78	58.06
58.89	59.44
60.56	61.11
61.39	61.67
62.22	62.78
62.78	63.06
64.44	64.44
70.00	70.00
70.28	70.56
72.78	73.33
73.89	73.89
80.00	74.44
80.56	81.11
81.11	81.67
81.94	82.22
82.22	82.22
82.78	82.78
83.06	82.78
84.17	83.89
89.44	90.00
91.11	91.11
94.72	95.28
96.11	96.67
98.89	98.89
99.44	100.00
100.00	100.28



BEST STRAIGHT LINE IS Y = 1.0072 X - .3208
MAXIMIM DEVIATION FROM B.S.L. IS .8111 DEG C.
RMS ERROR OF B.S.L. FIT IS .3433 DEG C.

Figure 8. Digital Calibration with Target Floating on Oil Bath

TABLE 5 - TEMPERATURE DROP - OIL BATH TO OUTSIDE OF CONTAINER

Gentle Stirring

Bath Temp ^oF	Outside Temp ^oF	T
146	143	-3
160	158	-2
170	167	-3
177	173	-4
190	187	-3
204	199	-5
217	216	-1
224	222	-2
229	225	-4

Violent Stirring

Bath Temp ^oF	Outside Temp ^oF	T
75	75	-0
80.5	80	-.5
87	87	0
90	90	0
111	111	0
120	119	-1
125	125	0
130	130	0
136	136	0
172	171	-1
201	200	-1
212	211.5	-.5

The first Telatemp 44 calibration using the 5.8 litre calibration standard was performed using water. Temperatures were varied between room temperature and the boiling point at the slightly elevated pressure possible in the covered source. The cover has since been vented and elevated pressures are no longer possible.

A .99 emissivity, the maximum emissivity selectable on the Telatemp 44, was assumed. The data are plotted in Figure 9. As in the Barnes test (see Figure 6), a negative peak in the deviation from best-straight-line occurs at 70°C (158°F) and a positive peak near 100°C (212°F). As in previous plots of digital readings, the ± 1 degree readout resolution makes the data appear to be somewhat erratic.

The next calibration was similar to the previous one except that analog readings were taken with a ± 0.1°C resolution, and the low end of the temperature range was extended down to 17.5°C (63°F). These data are plotted in Figure 10. The gain was very nearly equal to that of the previous calibration. However, the offset was -3.3166°C compared to +.6866°C in the previous calibration. This 4° difference is caused by an offset in a internal amplifier or in the analog to digital converter in the Telatemp 44.

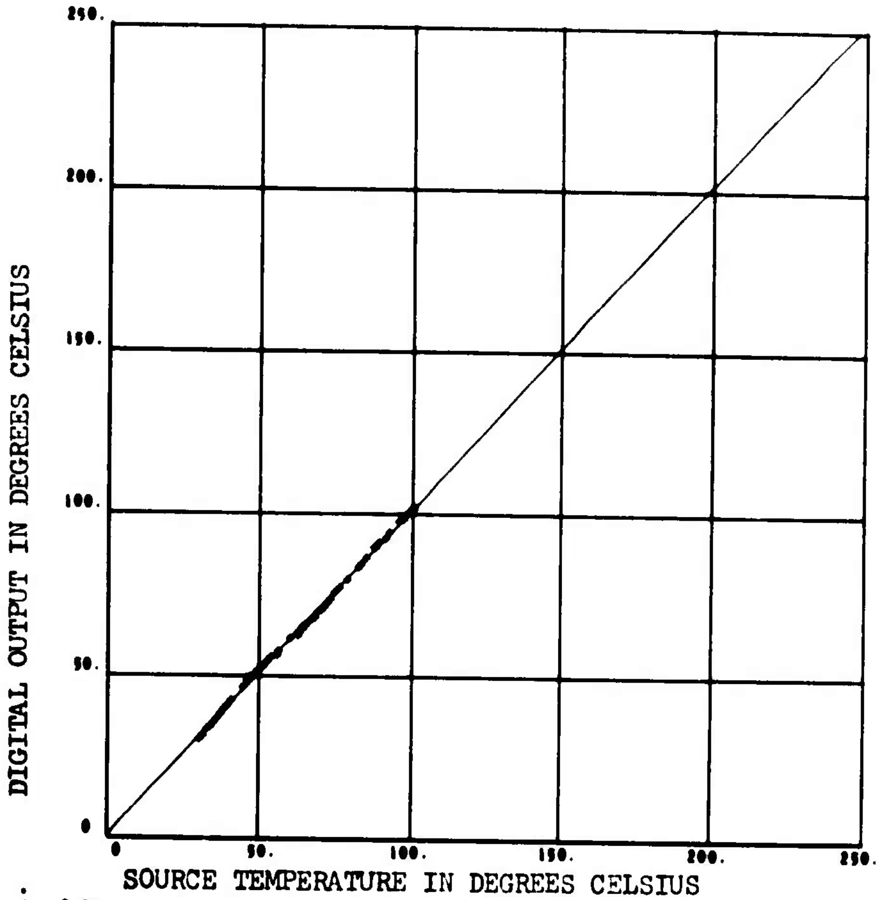
Note that the deviation curve is very smooth, characteristic of the fine reading resolution of the analog output. The deviation curve also has the same general shape as in Figures 6 and 7. Since the deviations plotted in Figures 6, 7, and 9 were from independent calibrations, this shape is characteristic of the Telatemp 44 and not a function of a particular calibration setup.

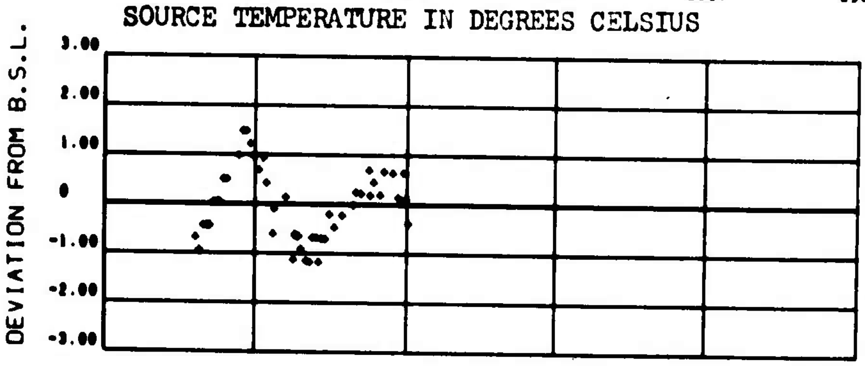
The final calibration was performed using the 8 litre standard. Motor oil was used as the fluid, allowing temperatures as high as 185°C (365°F). Emissivity was assumed to be .99.

Digital and analog readings were taken and are plotted in Figures 11 and 12. These data cover lower temperatures than the Barnes data, but not the higher temperatures. The shapes of the curves are in excellent agreement with other calibration curves, and offset values agree with the Barnes test. These results indicate that either the target emissivity value assumed is correct and the Telatemp 44 gain is 1.000, or a proper combination of errors exists to balance each other out. We conclude that the 8 litre standard has an emissivity very near unity (see Appendix A), and that the Telatemp 44 gain is very nearly 1.000.

The Telatemp 44 is capable of more precise measurements than advertised. Since the offset and deviation errors are consistent, the data in Figures 11 and 12 could be used as correction tables. Correcting the higher resolution analog readings should yield accuracies of ± 1°C over the 40°C to 185°C calibrated range in ideal conditions, especially when the target has an accurately known high emissivity (see Section III.A.).

X	Y
30.75	31.00
32.00	32.00
33.50	34.00
34.50	35.00
35.50	36.00
36.50	37.50
38.00	39.00
39.00	40.00
40.00	41.50
41.50	43.00
45.00	47.00
46.50	49.00
47.50	50.00
48.75	51.00
50.00	52.00
51.75	53.50
53.00	55.00
54.50	56.00
56.50	57.00
57.00	58.00
60.75	62.00
63.00	63.00
63.50	64.00
64.50	65.00
65.00	65.50
65.75	66.00
67.50	67.50
68.50	68.50
69.50	70.00
70.50	71.00
71.50	71.50
72.50	73.00
73.50	74.00
75.00	76.00
76.75	77.50
79.00	80.00
82.75	84.00
83.50	85.00
85.50	87.00
88.00	90.00
88.50	90.00
89.75	91.50
91.50	93.00
93.00	95.00
96.00	98.00
97.50	99.00
99.00	101.00
100.00	101.50
101.00	102.00

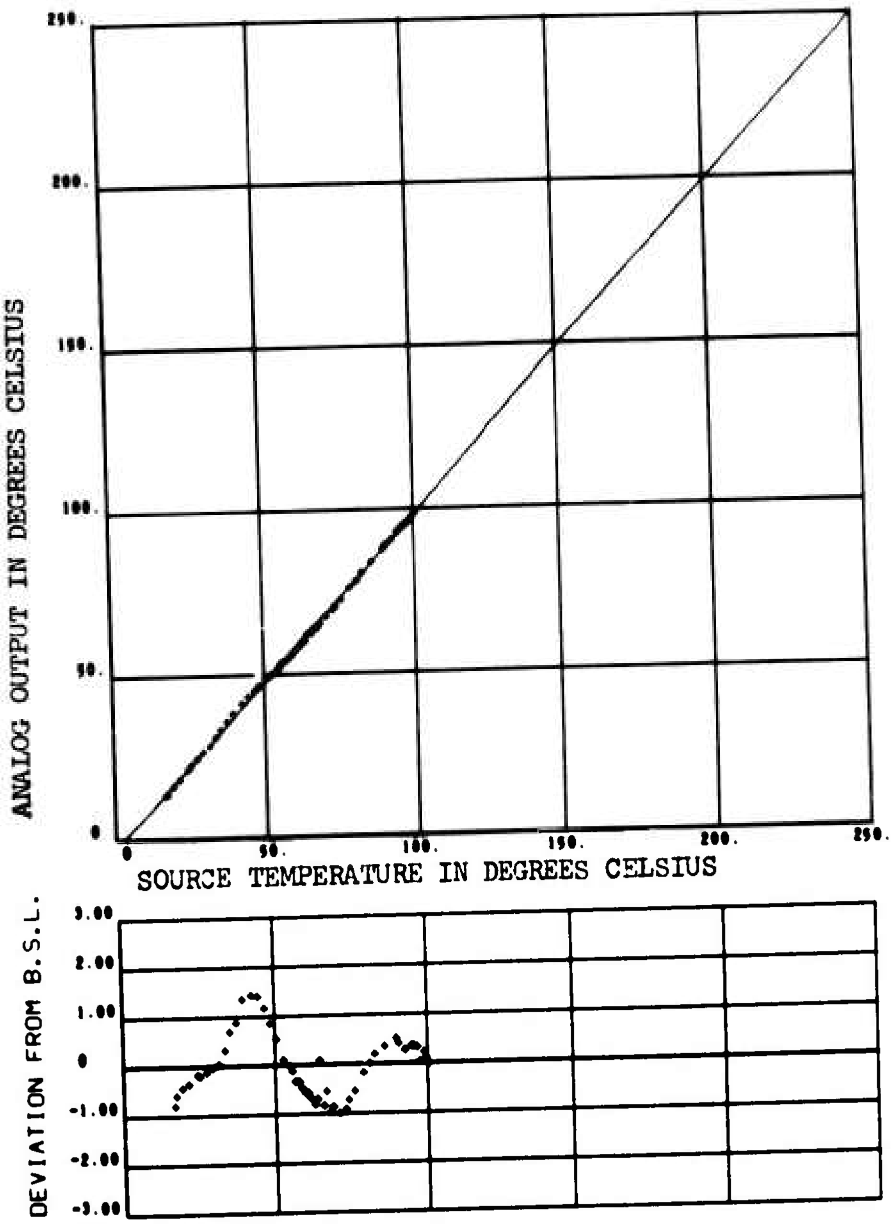




BEST STRAIGHT LINE IS Y = 1.0066 X + .6866
MAXIMIM DEVIATION FROM B.S.L. IS 1.5079 DEG C.
RMS ERROR OF B.S.L. FIT IS .6994 DEG C.

Figure 9. Digital Calibration with 5.8 Litre Standard

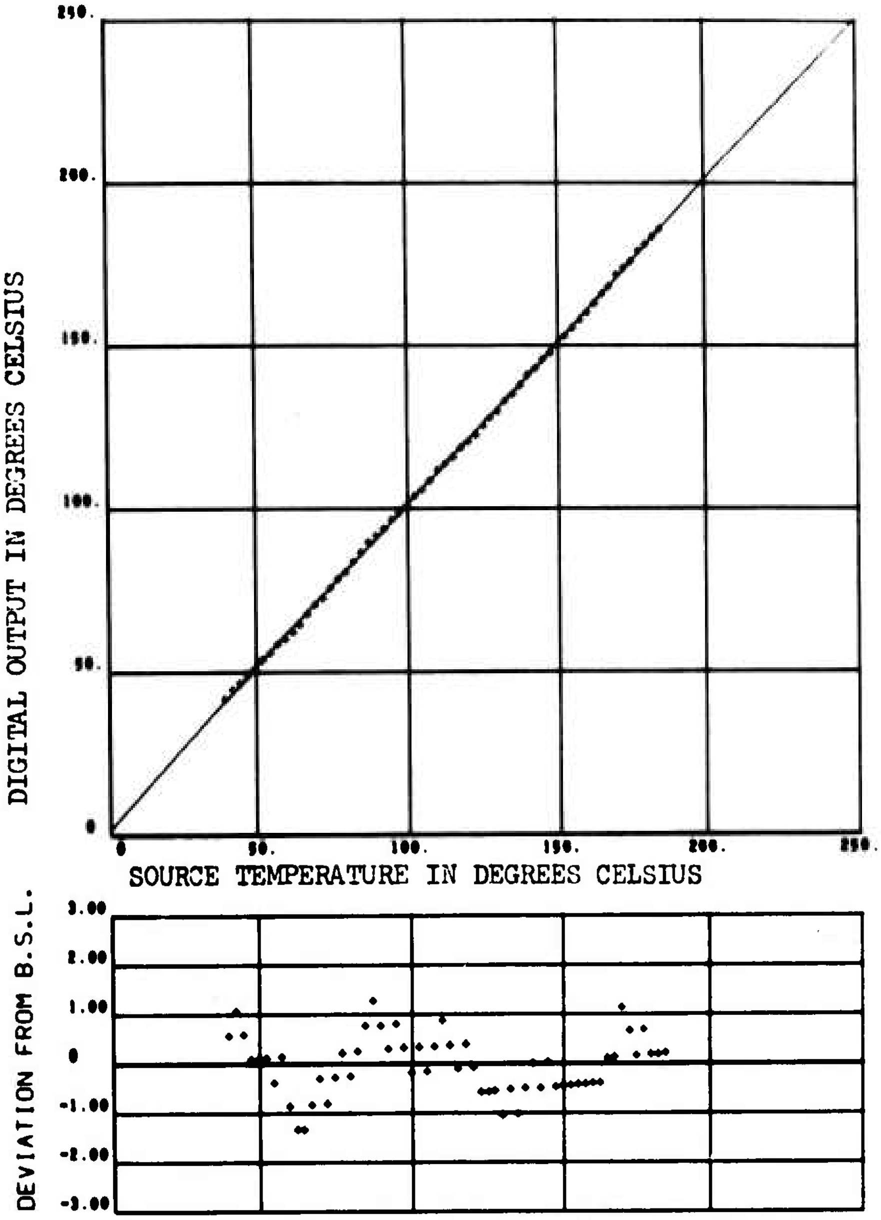
X	Y
17.50	13.60
18.00	14.30
20.00	16.50
22.00	18.60
25.00	21.80
26.00	22.80
28.00	24.90
30.00	27.00
32.00	29.10
34.00	31.40
36.00	33.80
38.00	36.00
40.00	38.50
43.00	41.60
45.00	43.60
47.00	45.90
49.00	47.10
51.00	48.80
53.00	50.40
55.00	52.30
56.00	53.20
57.00	54.00
58.00	55.00
59.00	55.90
60.00	56.80
61.00	57.80
62.00	58.70
63.00	59.60
64.00	60.70
65.00	62.50
66.00	62.60
67.00	63.90
68.00	64.50
69.00	65.60
71.00	67.50
73.00	69.60
74.00	70.80
76.00	73.00
79.00	76.90
81.00	78.60
83.00	80.80
86.00	84.00
90.00	88.20
91.00	89.10
93.00	91.00
94.00	91.00
95.00	93.10
96.00	94.10
97.00	95.10
98.00	95.80
99.00	97.00
100.00	97.90
101.00	98.80



BEST STRAIGHT LINE IS Y = 1.0109 X - 3.3166
MAXIMIM DEVIATION FROM B.S.L. IS 1.4500 DEG C.
RMS ERROR OF B.S.L. FIT IS .6148 DEG C.

Figure 10. Analog Calibration with 5.8 Litre Standard

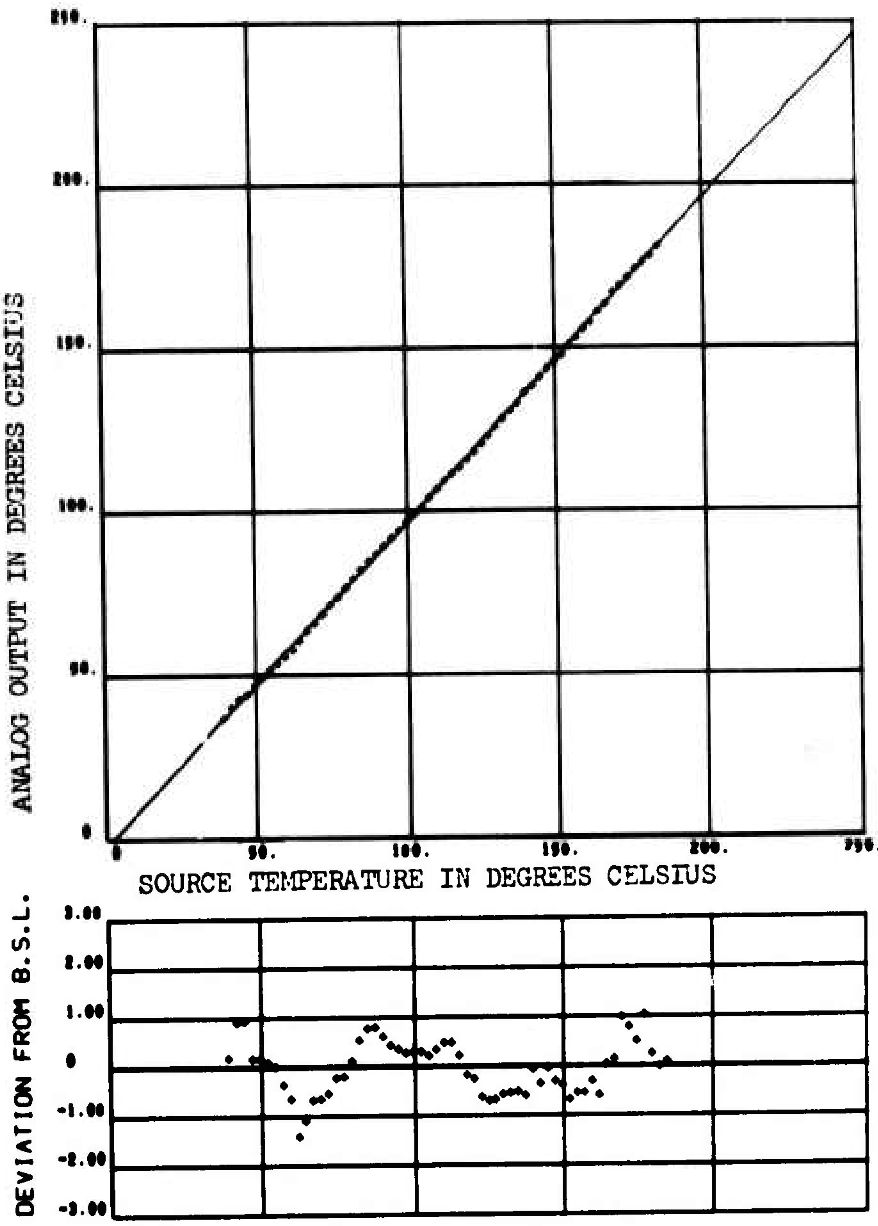
X	Y
40.00	42.00
42.50	45.00
45.00	47.00
47.50	49.00
50.00	51.50
52.50	54.00
55.00	56.00
57.50	59.00
60.00	60.50
62.50	62.50
65.00	65.00
67.50	68.00
70.00	71.00
72.50	73.00
75.00	76.00
77.50	79.00
80.00	81.00
82.50	84.00
85.00	87.00
87.50	90.00
90.00	92.00
92.50	94.00
95.00	97.00
97.50	99.00
100.00	101.00
102.50	104.00
105.00	106.00
107.50	109.00
110.00	112.00
112.50	114.00
115.00	116.00
117.50	119.00
120.00	121.00
122.50	123.00
125.00	125.50
127.50	128.00
130.00	130.00
132.50	133.00
135.00	135.00
137.50	138.00
140.00	141.00
142.50	143.00
145.00	146.00
147.50	148.00
150.00	150.50
152.50	153.00
155.00	155.50
157.50	158.00
160.00	160.50
162.50	163.00
165.00	166.00
167.50	168.50
170.00	172.00
172.50	174.00
175.00	176.00
177.50	179.00
180.00	181.00
182.50	183.50
185.00	186.00



BEST STRAIGHT LINE IS Y = .9954 X + 1.5976
MAXIMIM DEVIATION FROM B.S.L. IS 1.3127 DEG C.
RMS ERROR OF B.S.L. FIT IS .5874 DEG C.

Figure 11. Digital Calibration with 8.0 Litre Standard

X	Y
40.00	37.30
42.50	40.50
45.00	43.00
47.50	44.70
50.00	47.20
52.50	49.60
55.00	52.00
57.50	54.10
60.00	56.30
62.50	58.00
65.00	60.80
67.50	63.70
70.00	66.20
72.50	68.80
75.00	71.60
77.50	74.10
80.00	76.40
82.50	79.00
85.00	82.50
87.50	85.00
90.00	87.30
92.50	89.60
95.00	92.00
97.50	94.40
100.00	96.80
102.50	99.40
105.00	101.80
107.50	104.40
110.00	107.00
112.50	109.50
115.00	111.70
117.50	113.80
120.00	116.20
122.50	118.30
125.00	120.70
127.50	123.20
130.00	125.80
132.50	128.30
135.00	130.80
137.50	133.20
140.00	136.20
142.50	138.40
145.00	141.20
147.50	143.40
150.00	145.80
152.50	148.00
155.00	150.60
157.50	153.10
160.00	155.80
162.50	158.00
165.00	161.10
167.50	163.70
170.00	167.00
172.50	169.30
175.00	171.50
177.50	174.50
180.00	176.20
182.50	178.40
185.00	181.00



BEST STRAIGHT LINE IS Y = .9917 X - 2.5901
MAXIMIM DEVIATION FROM B.S.L. IS 1.3912 DEG C.
RMS ERROR OF B.S.L. FIT IS .5443 DEG C.

Figure 12. Analog Calibration with 8.0 Litre Standard

III.A.3. Repeatability

Repeatability is the precision to which an instrument will repeat the same reading for exactly equal quantities of a measurand. Lack of repeatability may take the form of reading scatter or degradation with the passage of time.

The Telatemp 44 repeatability is specified as $\pm 0.5\%$ of full scale, corresponding to $\pm 5^{o}F$ or $\pm 3^{o}C$. Repeatability was established by recording reading changes or drift with time, and by recording the effect of ambient temperature variations on readings.

For the drift test, the Telatemp 44 was mounted in an environmental chamber to control the ambient temperature. The source target was a heated metal block coated with a high emissivity paint. Temperatures of both the mass and the case of the Telatemp 44 were measured to $\pm 0.2^{o}F$ with thermocouples. The target block was heated and allowed to stabilize. The Telatemp 44 battery pack was fully charged prior to each test. Tests were run over two hour periods for each of two different target temperatures, $190^{o}F$ ($88^{o}C$) and $422^{o}F$ ($217^{o}C$). Test data appear in Table 6.

As the target emissivity was not accurately known, the errors between the Telatemp 44 reading and the measured target temperature are not significant. But variations in these errors characterize repeatability . Thus an average error was subtracted from the raw data providing variations which were then converted to a percent of target temperature, a measure of repeatability.

Repeatability was within $\pm 0.5\%$ of the reading, well within the advertised $\pm 0.5\%$ of full scale.

Another test was performed to find the effect that large ambient temperature variations might have on instrument repeatability. The same setup was used as in the previous test, except that the ambient temperature in the environmental chamber was cycled. After the first reading was taken, the ambient temperature was dropped from $70^{o}F$ to $50^{o}F$, raised to $100^{o}F$, returned to $70^{o}F$ and allowed to stabilize before taking the next reading. This sequence was repeated several times. Error variations were calculated as in the previous test. Again, the repeatability is well within the advertised $\pm 0.5\%$ of full scale.

TABLE 6 - REPEATABILITY AT FIXED CASE TEMPERATURE

Time	Telatemp Case Temp. °F	Target Temp °F	Telatemp Analog Reading °F	Analog Error °F	Analog Error Percent of Target Temp	Telatemp Digital Reading °F	Digital Error °F	Digital Error Percent of Target Temp
2:12	80.0	190.1	183.6	6.5	+.005	188	2.1	+.10
2:22	79.5	191.6	184.5	7.1	+.31	189	2.6	+.37
2:33	79.1	193.0	185.8	7.2	+.36	191	2.0	+.05
2:42	79.0	191.7	185.4	6.3	-.11	190	1.7	-.10
2:52	81.0	192.5	186.7	5.8	-.37	191	1.5	-.21
3:04	80.8	192.5	186.5	6.0	-.26	191	1.5	-.21
3:11	80.9	192.3	185.8	6.5	+.005	191	1.3	-.31
3:20	81.0	192.7	186.4	6.3	-.11	191	1.7	-.10
3:37	80.6	192.6	185.7	5.9	-.32	190.5	2.1	+.10
3:45	80.6	193.0	186.0	7.0	+.25	191	2.0	+.05
3:55	80.4	193.4	186.4	7.0	+.25	191	2.4	+.26
			AVERAGE ERROR = 6.509 Analog				1.900 Digital	
11:00	80.0	422.0	413.5	8.5	.03	418.5	3.5	.009
11:12	80.6	422.4	414.0	8.4	.006	419	3.4	-.015
11:27	80.6	422.8	414.0	8.8	.10	419	3.8	.08
11:44	81.1	422.9	414.7	8.2	-.04	419.5	3.4	-.015
11:59	80.9	422.6	414.3	8.3	-.02	419	3.6	.03
12:12	80.7	422.9	414.5	8.4	.006	419.5	3.4	-.015
12:20	80.1	423.0	414.8	8.2	-.04	419.5	3.5	.009
12:40	80.8	422.7	414.2	8.5	.03	419	3.7	.06
12:54	81.1	422.8	414.0	8.8	.10	419	3.8	.08
1:06	81.1	422.2	414.5	7.7	-.16	419.5	2.7	-.18
1:15	80.9	422.8	414.5	8.3	-.02	419.5	3.3	-.04
			AVERAGE ERROR = 8.373 Analog				3.464 Digital	

TABLE 7 - REPEATABILITY UNDER CYCLING

Cycles	Target Temp °F	Tele Analog °F	Analog Error °F	Error Percent of Target	Tele Digital °F	Digital Error °F	Error Percent of Target
0	156.0	146.6	-9.4	-.185	150.5	5.5	+.199
1	156.2	146.1	-10.1	+.263	150	5.8	+.391
2	156.6	147.0	-9.6	-.057	152	4.6	-.376
3	156.0	146.7	-9.3	-.249	150.5	5.5	+.199
4	156.8	146.6	-10.2	+.326	150.5	6.3	+.709
5	157.0	147.4	-9.6	-.057	152	5.0	-.120
6	157.2	148.2	-9.0	-.438	153	4.2	-.629
7	156.8	146.9	-9.9	+.135	152	4.8	-.248
8	157.0	146.9	-10.1	+.262	152	5.0	-.120
	Anal Avg Error=9.689				Dig Avg Error=5.189		

II.A.4. Resolution and Noise

Resolution is the smallest increment of a measurand an instrument can reliably detect. Random noise and quantizing errors in digital signals limit resolution.

The Telatemp 44 resolution is specified as ±.2% of full scale. For a full scale of 1000°F and 600°C, resolution corresponds to ±2°F and ±1.2°C. At 25°C (78°F) and at the lowest usable emissivity setting at this temperature, 0.6, the analog output resolution is about ±0.4°F and ±0.2°C when monitored on a digital voltmeter averaging over one second periods. At higher temperatures and emissivities, where the signal to noise ratio increases and the Telatemp 44 gain from the detector to output is reduced, the resolution is better than ±0.2°F and ±0.1°C.

The greatest resolution limiting factor is the quantizing error in the analog to digital conversion required for the digital display. The least significant digit is 1 degree. Thus, at best, the digital display itself leaves an uncertainty of ±0.5°. After adding in the contribution due to noise, the resolution at 25°C (78°F) is ±0.9°F and ±0.7°C. These figures fall within the specified ±2°F and ±1.2°C.

Figure 13 shows the noise on the analog output at various temperatures and emissivities. Figure 13-a represents the lowest practical temperature source which can be viewed at an emissivity setting of .11. Figures 13-b, c, and d show reduced noise due to higher source temperature at the same emissivity; and a low and a high temperature source at the maximum selectable emissivity.

During these noise tests, continued measurement of high temperatures produced a gradual increase in noise amplitude on the

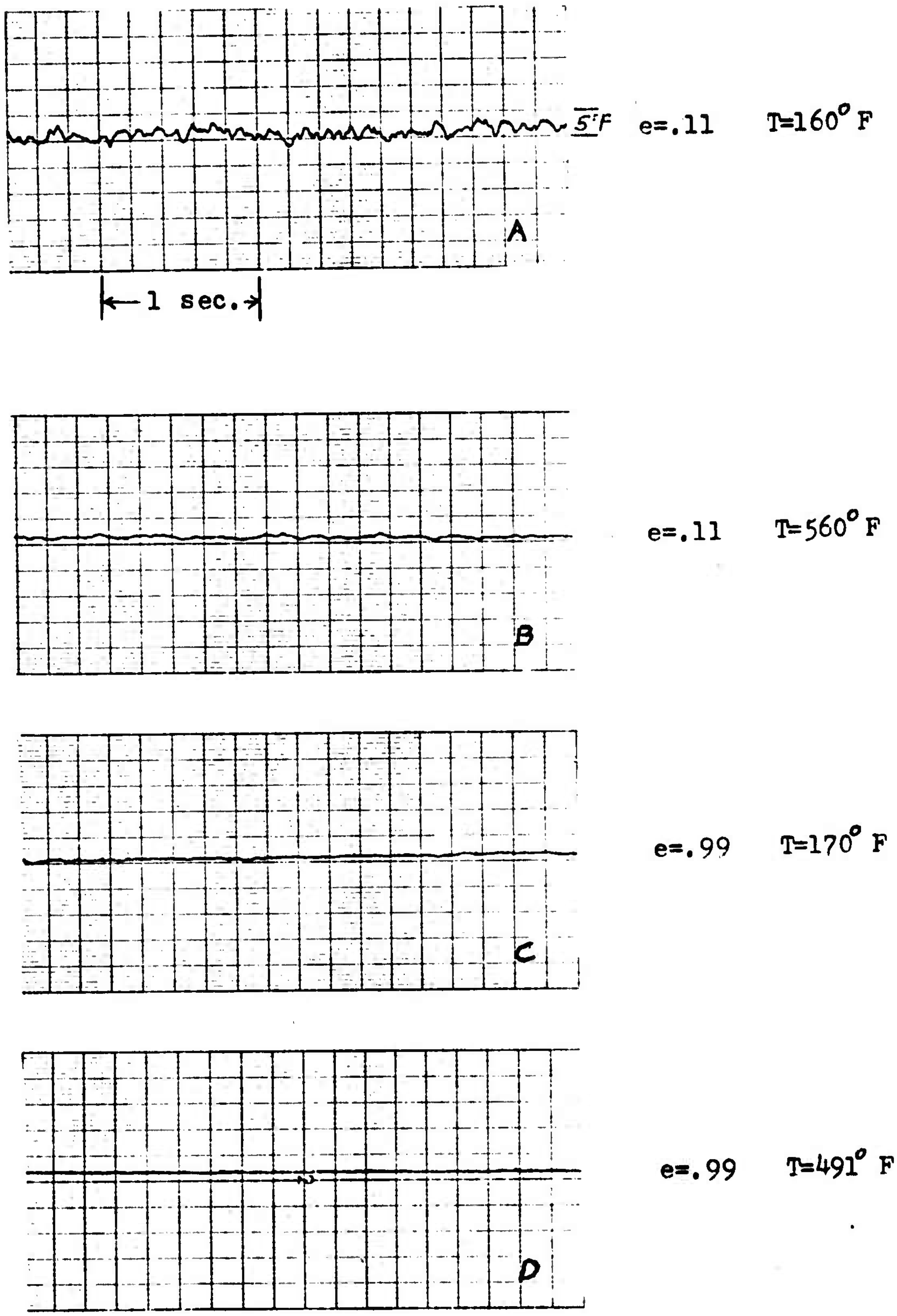


Figure 13 - Noise .vs. Emissivity and Temperature

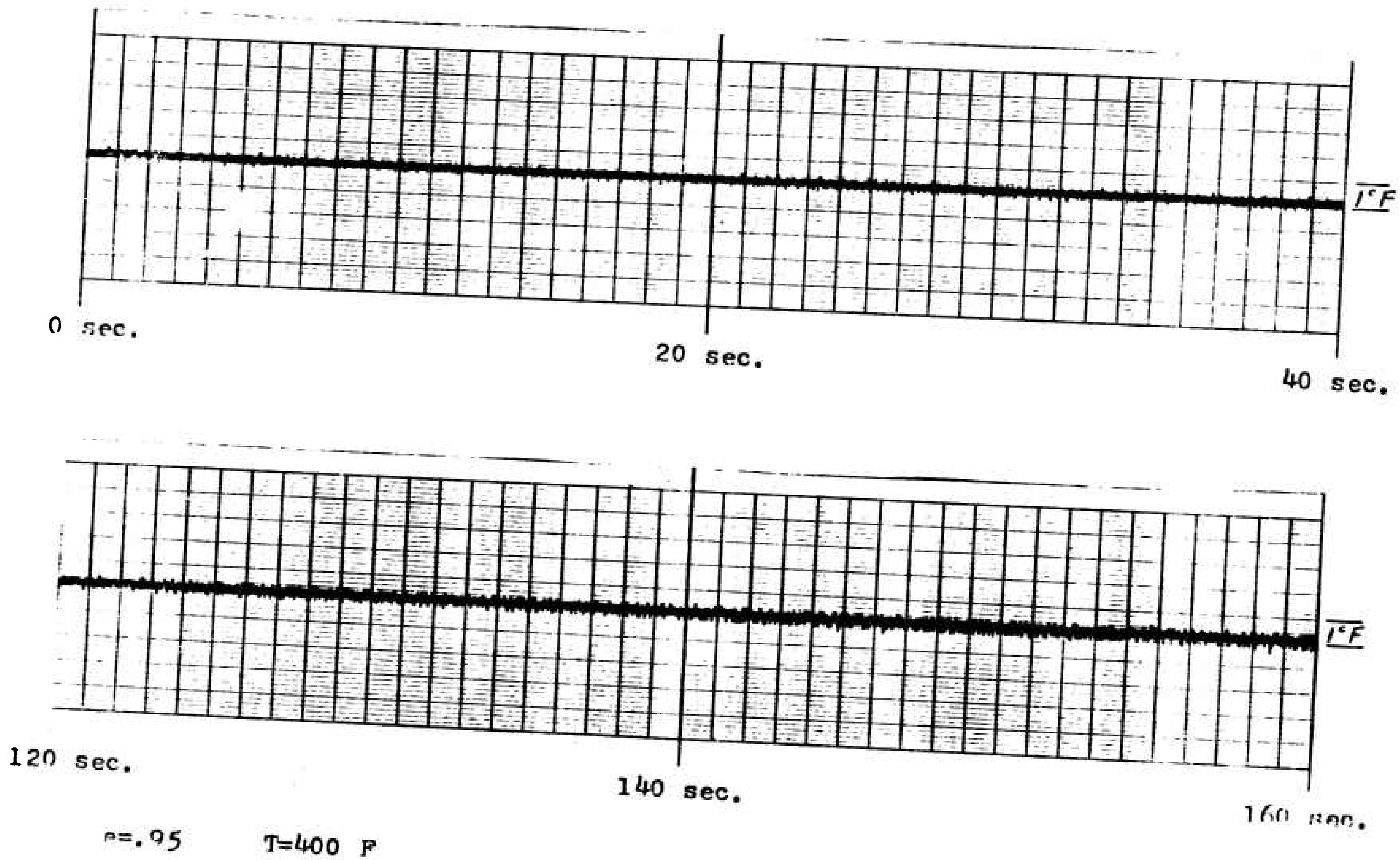


Figure 14 - Noise Increase With Time

analog output (see Figure 14). This figure shows the analog output during two 40 second periods two minutes apart. The source temperature was about 400°F (204°C) and the emissivity about .95.

The likely cause of this increased noise is that radiant energy being detected is heating the infrared detector. Heating the detector raises it's noise output.

Figure 15 further demonstrates the increase in noise with increasing ambient (and therefore detector) temperature. The measured source was held at a constant temperature of 100°F (38°C). An emissivity of .95 was assumed. The first half of the chart shows the noise on the analog output with the Telatemp 44 case temperature at 78°F (25°C). The second half of the graph shows the noise when the Telatemp 44 case was heated to 110°F (43°C).

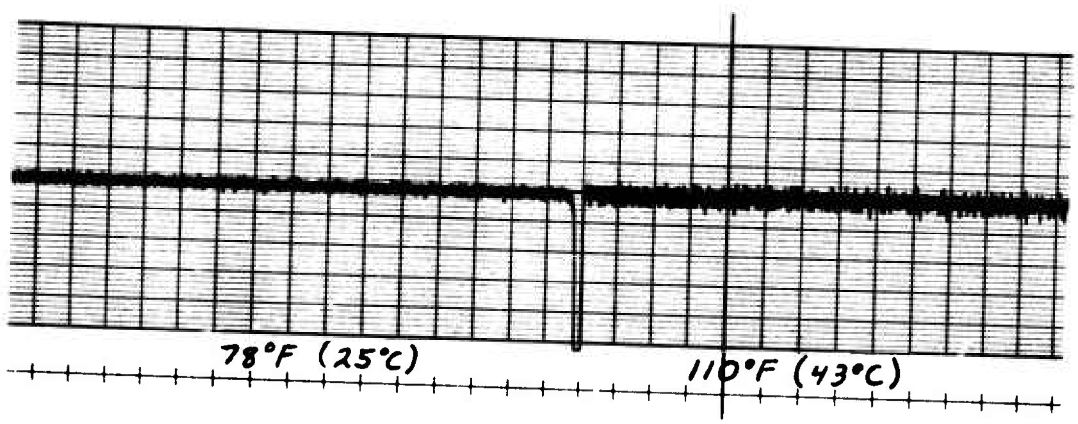


Figure 15 - Noise Increase With Case Temperature

II.A.5. <u>Linearity</u>

Telatemp 44 nonlinearity is specified as ±0.5% of full scale. This corresponds to ±3°C and ±5°F. Calibration data in the Accuracy section (see Figures 11 and 12) shows maximum deviations from the best-straight-line of about ±1.4°C (±2.5°F) over the limited range measured. This deviation pattern is due primarily to the diode shaped amplifier gain curve.

II.A.6. Response Time

The Telatemp 44 response time is specified as less than 50 milliseconds for the "Hot-Spot" (and analog) outputs and one second for digital readings. This is true for changes from one temperature to another; but response time including unit turn-on time is much longer.

A test was performed to determine the settling time for analog and digital outputs after the Telatemp 44 is turned on. Strip chart recordings were made of the analog output. Timing marks corresponding to the times the pistol grip turn-on contacts were closed and when the digital output stabilized were also recorded. The test was repeated for various target temperatures.

The results show that analog readings stabilize within four seconds, while the digital output required seven seconds to stabilize.

II.B. OPTICAL TESTS

II.B.1. Target Spot Size

The spot size is specified as less than one twentieth of the distance from the measured spot to the instrument's focal plane. The example given, and applicable to this unit, is 1½ inch spot size at 30 inches (3.8 cm at 76 cm). Experience with this unit has shown that an area with a temperature much higher than the target temperature, inside a 2½ inch diameter concentric circle, but outside the 1½ inch target area, can produce significant error. This larger 2½ inch target is required for confidence (see Figure 16).

The existance of this fringe is due in part to imperfect baffling of the detector and in part to the reflection from the inner walls of the case.

II.B.2 Focal Distance

The focal distance for this Telatemp 44 was factory set to the standard 30 inches. No test was performed to confirm this.

II.B.3. Spectral Response

Facilities were not available to measure the spectral response of the Telatemp 44. The spectral response should be the products of the spectral response of the detector, the spectral transmission of the polypropylene dust protector, and the spectral reflectivity of the primary and secondary mirrors. Spectral response is discussed in greater detail in Section IV.C.

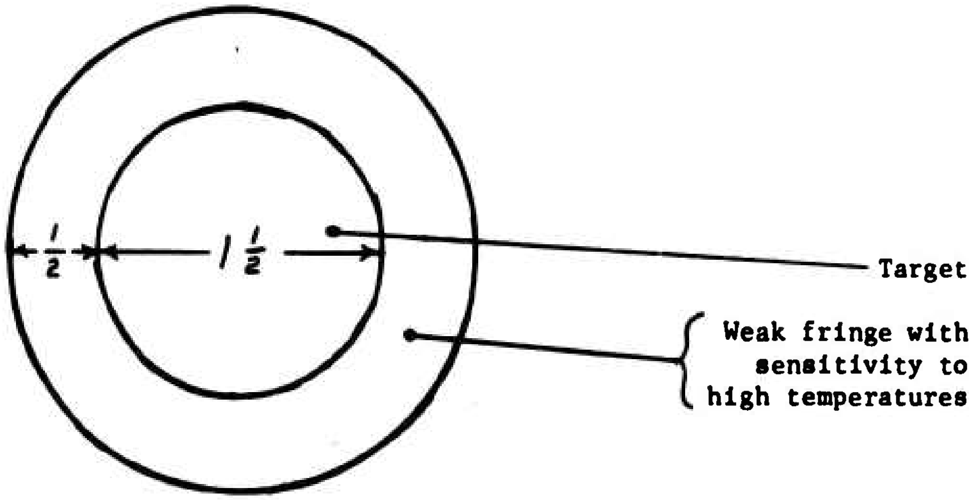


Figure 16 - Target Spot Size

II.B.4. Electro-optical Bore Sighting

The manufacturer suggests aiming the Telatemp 44 by sighting along ribbed extrusions on the case. Then using the hot-spot detector as a guide, the direction of maximum readings can be found. This procedure can be quite effective, but only if the area of interest is the hottest area in the vicinity.

If the hot-spot detector cannot be used, one must know that the optics are properly aligned. A test was performed to determine the precise target point when the extrusions indicated in Figure 17 are assumed to define axis.

The detector to target distance in this optics alignment test was 30 inches (76 cm). The detector was aimed at the center of a sheet of polar-coordinate paper. An incandescent light bulb was moved around the paper until the highest analog reading was observed and this position was noted. Five readings were taken with the Telatemp 44 held upright and five with it rotated 90°CCW. The readings were then averaged. The actual location of the most sensitive area is 0.52 cm (0.205 in.) left of and 0.85 cm (0.333 in.) high of the aiming point. In practical applications these differences should cause no problems.

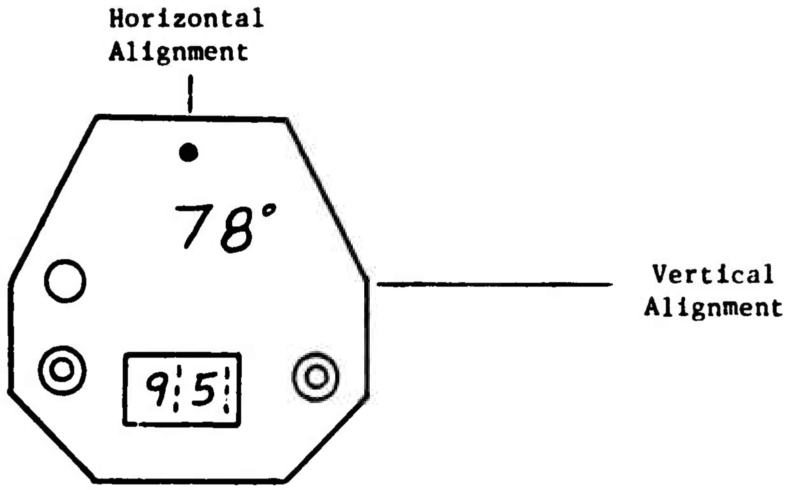


Figure 17 - Extruded Aiming Sights

Using the recommended aiming technique and the hot-spot detector provides a satisfactory means to focus on the desired target. Only "through-the-lens" viewing would be more effective. A separate bore-sight would be subject to parallax errors and place a restriction on distance to the target. This is in addition to that already imposed by the dependence of spot size on the detector-to-target distance.

II.C. OUTPUTS AND CONTROLS

II.C.1. Outputs

In addition to the 3-decade digital temperature display, an analog output provides one millivolt per degree. The analog output gives better resolution than the digital readings. There is, however, a four to five degree (or millivolt) offset error at the analog output, probably generated in the buffer amplifier. Readings appear to be lower by this offset.

A decimal point appearing to the right of the °F or °C markings on the digital display indicates weak batteries. However, the unit gives totally erroneous readings within one minute after the low battery warning appears. This is a very short grace period. Readings should not be taken after the warning appears.

II.C.2. Emissivity Adjustment

Two decades of thumbwheel switches allow emissivity settings from .10 to .99 in .01 increments. This range is more than adequate since other considerations lead to restricting the normal use of the instrument to high emissivity (0.9 or greater) targets.

II.C.3. Zero Drift Control

The Telatemp 44 is specified as having automatic compensation for zero drift. The Telatemp 44 passed the previous repeatability test. However, in the environmental test results shown in Figure 18 the unit was shown to drift considerably if outside the 40-110°F (4-43°C) ambient temperature range.

II.C.4. Bias Control

The hot-spot bias control permits the adjustment of the "minimum-on" temperature from about 50° to 500° C or F. This range is satisfactory for nearly all applications. The knob, however, is small and difficult to adjust critically.

II.C.5. On-Off Control

Power is applied to the electronics automatically. The operator's hand completes an electrical circuit between two gold plated contacts on the handgrip which triggers a power enable circuit. It is possible but unlikely that an operator could grasp the handgrip and not complete the electrical circuit.

A test was run to determine the maximum resistance between contacts which will still allow the power enable circuit to reliably trigger. The Telatemp 44 was mounted in the environmental chamber. Over the range of 40°F to 110°F (4-43°C) the maximum turn-on resistance was determined for three powering conditions. They are (1) fully charged batteries and still on charge, (2) fully charged batteries, no charger, and (3) batteries with four hours of operation.

Turn-on was independent of temperature over the range tested. Slightly different maximum resistances are noted for the three conditions; (1) less than 5.2 megohms (2) less than 5.1 megohms, and (3) less than 5.0 megohms. Turn-off occurs when resistance is increased to greater than 5.4 megohms in all conditions.

To determine if the human hand can satisfy these requirements, resistance characteristics of a hand were studied. The contacts on the Telatemp 44 handle were insulated, and new contacts were glued to the insulating tape at these same locations. A Megohmeter was used to measure the hand resistance between the new contacts. Following is a list of conditions and resistances observed.

(1)	Hand at room temperature, first contact	200K
(2)	Hand at room temperature, after carrying 1 min	100K
(3)	Hand at 35^{o}-40^{o}F, first contact	5 Meg
(4)	Hand at 35^{o}-40^{o}F, after carrying 1 min	2.5 Meg
(5)	Hand at 50^{o}-55^{o}F, first contact	500K
(6)	Hand at 50^{o}-55^{o}F, after carrying 1 min	150K
(7)	Finger tip holds, hand warm	1-2 Meg
(8)	Finger tip holds, hand cold	4-5 Meg

In the operating limits of the Telatemp 44, there should be no difficulty achieving turn-on due to hand resistance.

It is possible to accidently turn-on the Telatemp 44 when carrying by its body if the hand comes in contact with the front strip.

II.D. ENVIRONMENT

The nonoperating environment is specified as 0^{o}F to 150^{o}F (-18^{o}C to 66^{o}C). Establishing the reliability of the instrument after storage at the extremes of this range would require some knowledge of the components of the Telatemp 44. Only destructive testing would establish the actual limits. The specified limits have been achieved with no apparent harmful effects.

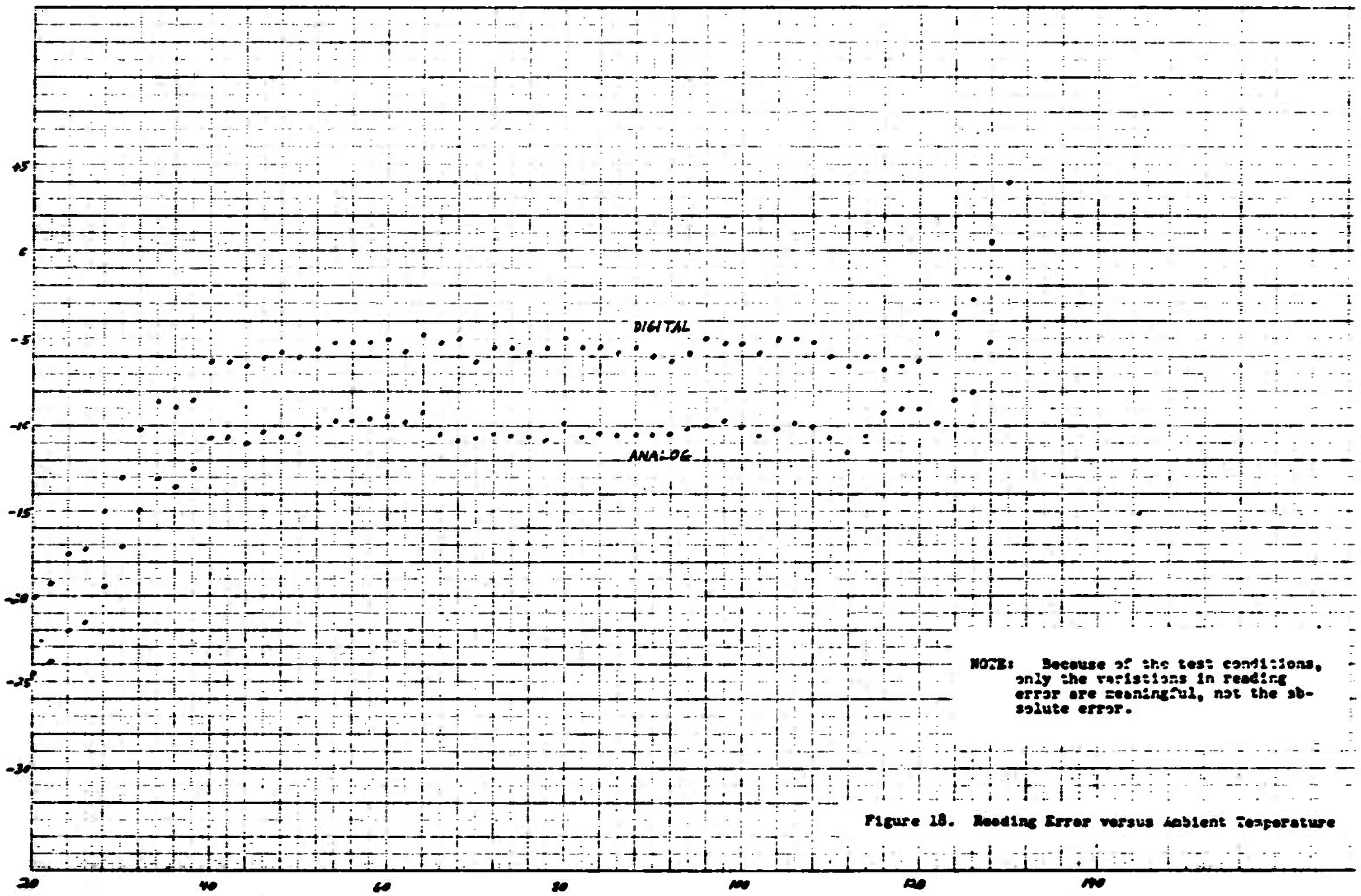
The Telatemp 44's operating environment is specified as 35^{o} to 120^{o}F (2^{o} to 49^{o}C). A test was run to determine the practical operating temperature range. The Telatemp 44 was mounted inside an environmental chamber "looking" out at a heated target. A mirror installed on the back surface of the environmental chamber allowed the display to be read from outside the chamber. The batteries were kept fully charged throughout the test.

The target was heated to 135^{o}F (57^{o}C). The chamber and the Telatemp 44 were then cooled to $+18^{o}$F (-8^{o}C) and heated to 130^{o}F (54^{o}C). Analog and digital Telatemp 44 readings of the target's temperature were taken at each 2^{o}F increment in chamber temperature.

As with the repeatability test, absolute accuracy was not important, only the stability and repeatability.

The data plotted in Figure 18 show serious deviations immediately outside the specified 35-120^{o}F (2-49^{o}C) ambient temperature range. The best results were achieved in the 40-110^{o}F (4-43^{o}C) range, and this should be used as the practical operating range.

No vibrational specifications are given by the manufacturer. No attempt was made to establish any since any such testing could be destructive or cause misalignment. The instrument appears to be rugged with the possible exception of the optics. If this instrument is dropped or exposed to extremes of temperature, it should be realigned or recalibrated.



Reading error °F

Case Temperature °F

Figure 18. Reading Error versus Ambient Temperature

Even though reasonable humidity will not effect the electronics, it does effect energy transmission in the optical path between the detector and target. High humidity can effect the calibration of the instrument. Humidity effects will be treated in Section IV, Limitations.

The worst case of water vapor effects occurs when a cold Telatemp 44 is taken into a hot, humid area. Any fogging of the polypropylene sheet renders useless any readings taken until the fogging is removed.

II.E. <u>POWER SOURCE</u>

Nickel-cadmium batteries supply power to the Telatemp 44. The specified four hours of continuous use is conservative; six hours is possible. Battery load is dependent on the digital reading. The display requires 3½ times the power to display "888" as it does to display "111." The display represents a considerahle percentage of the power drain.

The specifications state, "operahle from AC line power and while charging." This implies that there are two modes of operation: (1) while charging (charger hooked to AC power), and (2) "from AC line power" (which to be distinguished from (1) would imply no charging or no batteries). This is somewhat misleading. If for example a battery cell fails and operation is desired, one may be tempted to remove the batteries and use the charger to power the thermometer. However, the output of the charger is not filtered and should not be applied to the Telatemp 44 without the batteries installed. The batteries serve as the filter when the charger is plugged in.

The specifications should read "operable from AC line power while charging."

II.F. <u>FAILURE REPORT</u>

While preliminary tests were being performed on the Telatemp 44, an operational defect was noted. When a target in excess of about 550^{o}F (288^{o}C) was viewed, erratic digital readings were observed. A monitor on the analog output showed positive going spikes on this normally smooth signal, see Figure 19.

The instrument was returned to the manufacturer for repair. Repairs were made quickly. The defect has not reoccurred. The malfunction was caused by an intermittent component.

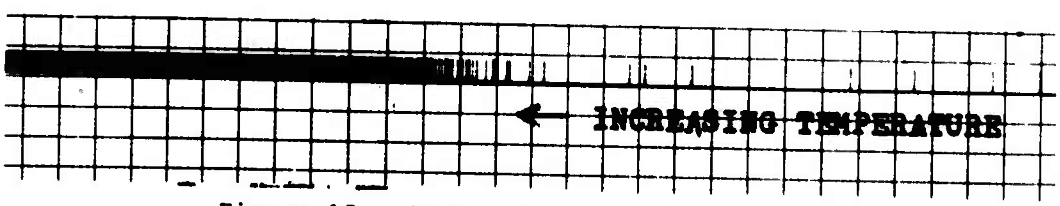


Figure 19. Analog Output During Failure

SECTION III - LIMITATIONS

Three factors control the usefulness of IR thermometry; surface emissivity, target area, and thermometer resolution.

III.A. EMISSIVITY

Perhaps the most difficult problem encountered in infrared thermometry is determining the surface emissivity. Surface emissivity is defined as the ratio of the energy emitted from a surface to that energy emitted from a blackbody at the same temperature. A surface with .75 emissivity will radiate 75% of the energy radiated by a perfect radiator at the same temperature. Since a good radiator is also a good absorber, a .75 emissivity surface will absorb 75% of the radiant energy it intercepts. It reflects the other 25%.

Thermal radiation, the basis for IR temperature measurement, is dependent on several factors in addition to the target material and temperature. Surface emissivity is a function of the material, it's texture, and surface impurities and their thickness.

Simple tables give total emissivities of a material at a few temperatures and for a few compositions. Texture is seldom specified and thickness of the oxidation layer almost never. Tabulated emissivities for materials, are often not applicable to the arbitrary targets found in IR thermometry. Theoretically the maximum reading accuracy should be obtained from the Telatemp 44 when its emissivity setting corresponds to the actual surface emissivity. However the thermometer responds to a weighted average emissivity because of its band limiting optics. Therefore less than satisfactory results are often obtained when emissivity values from standard tables are set into the thermometer's dial. This is especially true if the emissivity is low.

Ideally the emittance of each target would be determined prior to each measurement. This procedure would negate the convenience of using IR thermometry for temperature measurements.

Since a precise value of emissivity may not always be available, one should know the error which results from improper emissivity settings.

A test was performed to determine reading error as a function of emissivity setting. Targets with emissivities of about .25, .5, and .95 were viewed by the Telatemp 44. A nominal target temperature of 150°F (66°C) was used. The actual target temperature and the analog Telatemp 44 readings were recorded as the emissivity switch was set to different values. The errors were determined and plotted in Figure 20.

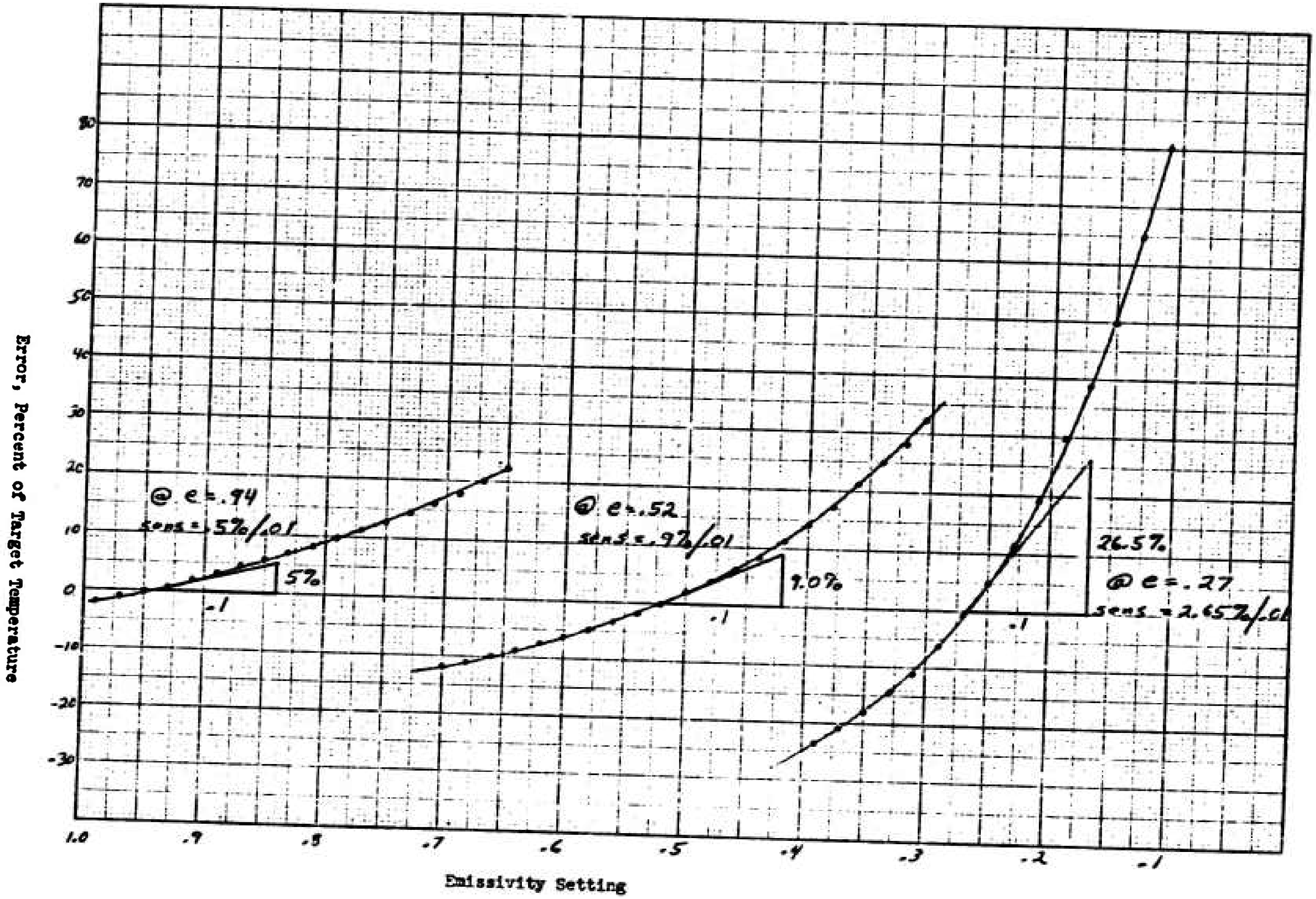


Figure 20. Reading Error versus Emissivity Setting

These curves show that the sensitivity to emissivity setting (the slope of the curve) is less at higher emissivities. This is one of several reasons for preferring high emissivity targets.

Emissivity is affected by surface contamination. If the target cannot be kept free of surface contamination, contamination effects should be minimized. A high emissivity target will be less effected by contamination than a low emissivity target.

Two mechanisms account for most contamination. They are oxidation or tarnishing and coating with organic substances.

Oxidation or tarnishing causes irreversible changes in surface emissivity. Oxidation is accelerated by high temperatures. Metals generally exhibit higher emissivity at higher temperatures even if no oxidation occurs. Certain oxidized alloys will exhibit a lower emissivity at some intermediate temperature and a higher emissivity at lower and higher temperatures. Materials which are continuously cycled in temperature, and are monitored over a range of temperatures, must be coated with a high emissivity paint or a coating which has an emissivity which is insensitive to temperature changes.

All organic contaminates exhibit characteristic windows of transmission to some extent, usually inversely to their thickness. A coating of oil, a common shipboard organic contaminant, if sufficiently thick to be opaque in the Telatemp 44's 2-15 micron range, will exhibit an emissivity around .95. But such thicknesses could insulate the target from an IR thermometer. Thinner films are more transparent, and exhibit emissivities more characteristic of the substrate metal. Thus uncontrolled, unknown organic contamination may not reliably provide a high emissivity surface on low emissivity materials. However, thin organic contamination does not seriously change characteristics of a high emissivity surface.

For practical considerations IR thermometry targets in a shipboard atmosphere must have high initial emissivities. Painting is the most convenient way to produce high emissivities. Two commercial paints have been recommended for this purpose: Krylon Ultra Flat Black, made by Borden, Inc.; and 3M's Nextel Velvet Coat. The Krylon product has an emissivity of 0.93, and the 3M product 0.97. While the 3M paint has the higher emissivity, it has a very fragile and rough surface which cannot be readily cleaned, thus it would not be suitable for shipboard use.

The Krylon paint was tried. In fact, it was used extensively throughout evaluation of the Telatemp 44. It is readily available. It is quite opague and easily provides a high, known emissivity with a thin coat. It maintains a 0.93 emissivity at temperatures up to 350°F (177°C), although the surface softens above 300°F (149°C). Above 350°F the paint is permanently damaged.

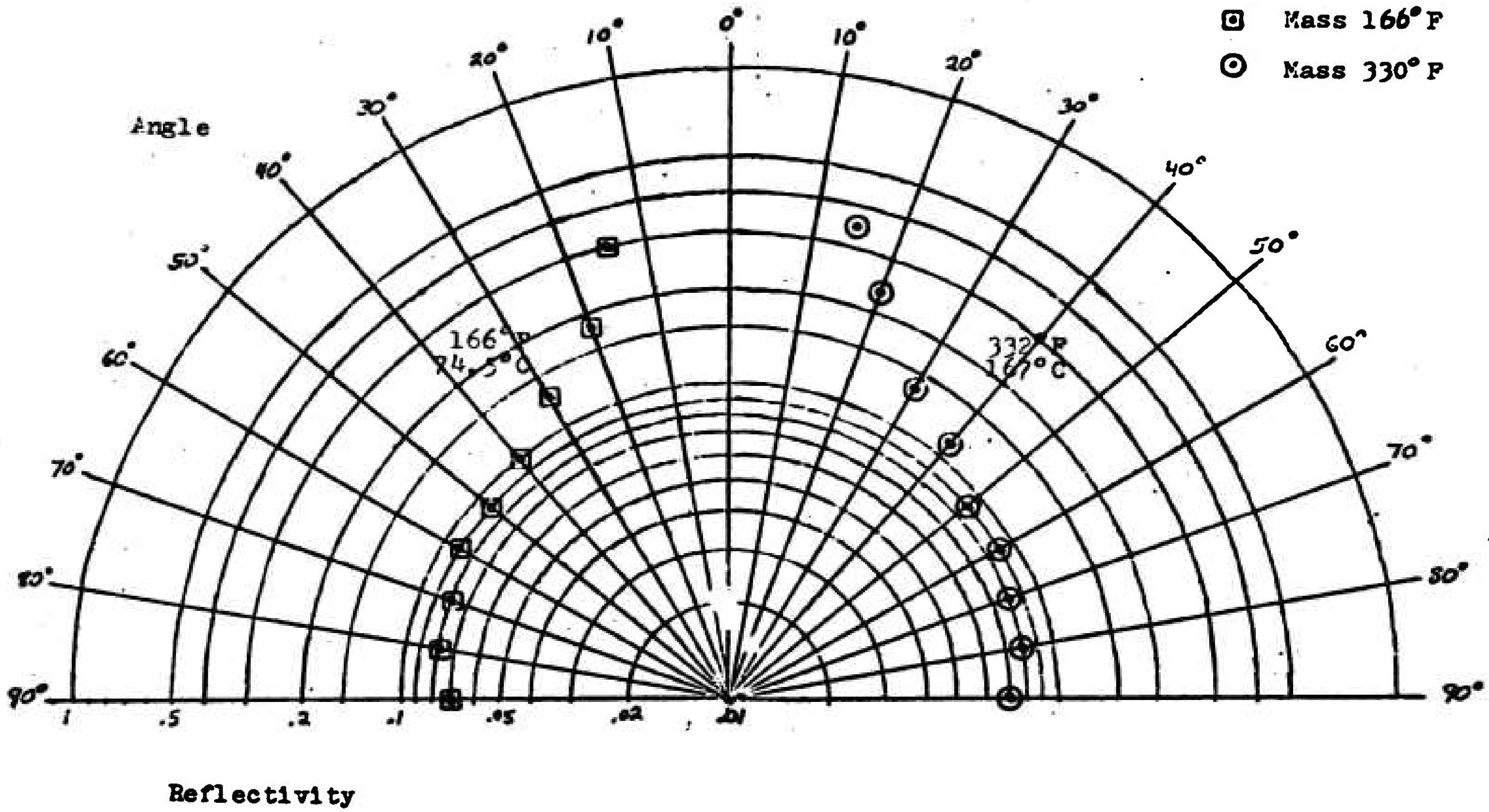


Figure 21. Reflectivity Versus Viewing Angle

While the Krylon Ultra Flat Black is more practical to use than the 3M Nextel Velvet Coat, its smoother texture will exhibit a greater emissivity variation with different viewing angles (the angle between the Telatemp 44's line of sight and the viewed surface). These variations were investigated. An aluminum plate was painted with the Krylon and heated. The Telatemp 44 was held at 90° (perpendicular) to the surface and its reading recorded. Then at various other angles the emissivity switch was readjusted to produce the same temperature reading as at 90°. This emissivity setting was then substracted from unity to give reflectivity. Data were taken at two different target temperatures, 166°F (74.5°C) and 322°F (167°C), and plotted in Figure 21.

The two graphs, which compare well, can be used to establish how far from normal is an acceptable angle for viewing the surface. Consider that each .01 error in emissivity represents an error of about .5% of the reading.

A flat normal surface will exhibit an emissivity which is precisely the normal emissivity of the surface. A convex surface will exhibit an emissivity less than the normal emissivity. A concave surface will exhibit a higher emissivity, the limiting case being the interior of a sphere which has an emissivity of 1.000.

If the Telatemp 44 is used to measure the temperature of sloping or curved surfaces painted with Krylon Ultra Flat Black, the plot in Figure 21 may be used to determine the proper emissivity switch setting. Assuming a flat surface 60° to the line of sight, the reflectivity is about 0.09, thus the emissivity is about 0.91. Emissivities for curved surfaces are more difficult to judge. Consider a 2 inch pipe as shown in Figure 22. Although the viewing angle seen by the 1½ inch major beam varies from 90° (e = 0.93) to about 41° (e = 0.90), a much greater proportion of the viewed spot is near 90° than 41°. Thus the assumed average emissivity should be weighted toward the 90° value, perhaps 0.92.

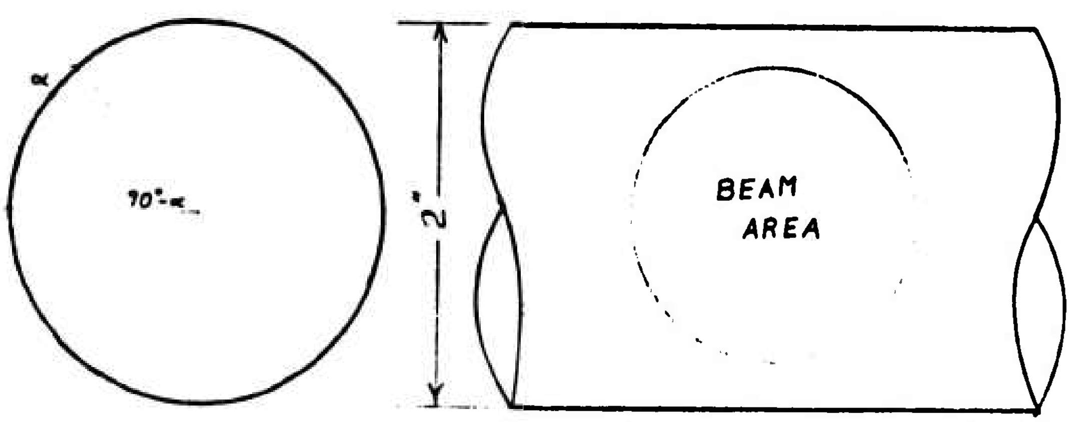


Figure 22 - Beam Incidence on 2" Pipe

Pipes significantly larger than 2 inches can be treated as a flat plate. Pipes much smaller cannot be accurately measured with the Telatemp 44 without adding a larger target.

Discussions so far ignore the effects of reflected energy. This is generally permissible if (1) the surface emissivity is high and (2) the viewed target is hotter than the surroundings. Worst case operation is experienced when both of the above are reversed. A cold, low emissivity surface may emit less energy than it reflects from warmer surroundings.

The following test gives an indication of how serious this problem can be. An aluminum plate, half painted black,half natural was cooled to 0°F (-18°C). Its emissivity was determined roughly by using a light source and detector. Values of reflectivity determined were 0.75 for the natural aluminum and 0.06 for the painted surface. Both values are in the range anticipated for infrared emissivities, 0.25 for the natural aluminum and 0.94 for the painted surface. Table 8 shows the results of this experiment.

TABLE 8 - REFLECTIVITY ERRORS

Reading No.	Target Surface	Emissivity Setting	Plate Temp	Tele Reading	Background Temp
1	painted	.94	0°F	3°F	82°F
2	natural	.94	0°F	68°F	82°F
3	natural	.25	0°F	120°F	82°F
4	painted	.94	250°F	252°F	82°F
5	natural	.94	250°F	130°F	82°F
6	natural	.25	250°F	258°F	82°F

The background temperature was obtained by aiming the Telatemp 44 away from the target in the general direction from which reflected energy would originate.

If the instrument was not calibrated to compensate for reflected energy at some assumed background temperature, all readings will be high, even if insignificantly high.

Only slightly high readings are recorded for the painted surface. However, at any emissivity setting, unacceptably high readings are recorded for the natural side of the target.

Consider reading number 3, natural aluminum at 0°F and emissivity set to the proper value of 0.25. Using the Stefan-Boltzmann law, the

82^oF background is radiating $(\frac{542^oK}{460^oK})^4 (\frac{0.94}{0.25}) = 7.25$ times as much energy as the 0^oF aluminum plate. Since the aluminum's reflectivity is 0.75, 75% of the background radiation intensity will be reflected toward the infrared thermometer. Thus the thermometer will receive 5.4 times as much energy from the background as from the intended target. Although this represents gross radiated energy and does not take into account the spectral characteristics of the IR thermometer's optics or detector, it does show the magnitude of the problem and why the Telatemp 44 would be expected to read high when attempting to measure the temperature of a cold, low emissivity surface. These readings are, of course, out of specification for the instrument.

Arithmetic compensation for reflected energy would be a laborious if not impossible task. A very detailed study of the detector, the optics, the shield of polypropylene and the gain functions of the Telatemp 44 and the radiated spectral energy from the target body and background would be required to predict with any regularity the reading error when reflected energy is significant compared to emitted energy.

Compensating for reflected energy is not recommended. Rather, all attempts should be made to maximize the target emissivity to a sufficiently high value that reflected energy can be ignored.

A point to consider, particularly in conjunction with outside temperature measuring, is that a high emissivity, low reflectivity target also has a high absorptivity. This means that other hot masses, the sun being one, radiate energy which will be absorbed by the target. If the object to be measured does not have significant thermal mass, or heat capacity, to store the absorbed energy, its temperature will rise. Target radiation in these cases will not represent the temperature measurement desired. This is the converse of the situation where the target presents an area where significant energy is removed from the mass whose temperature is to be measured.

III.B. Target Size

The Telatemp 44 thermometer accumulates energy emitted from the surface of the target material. The larger the thermometer's target spot size, all else being equal, the more sensitive the device is. That is, a large target thermometer can focus more energy on its detector than a smaller target thermometer, thus a higher detector output. The higher the detector output at a given temperature, the less the gain required to convert the output to a selected analog voltage level. Higher gain amplifiers will, of course, amplify detector noise levels by a proportionally larger amount.

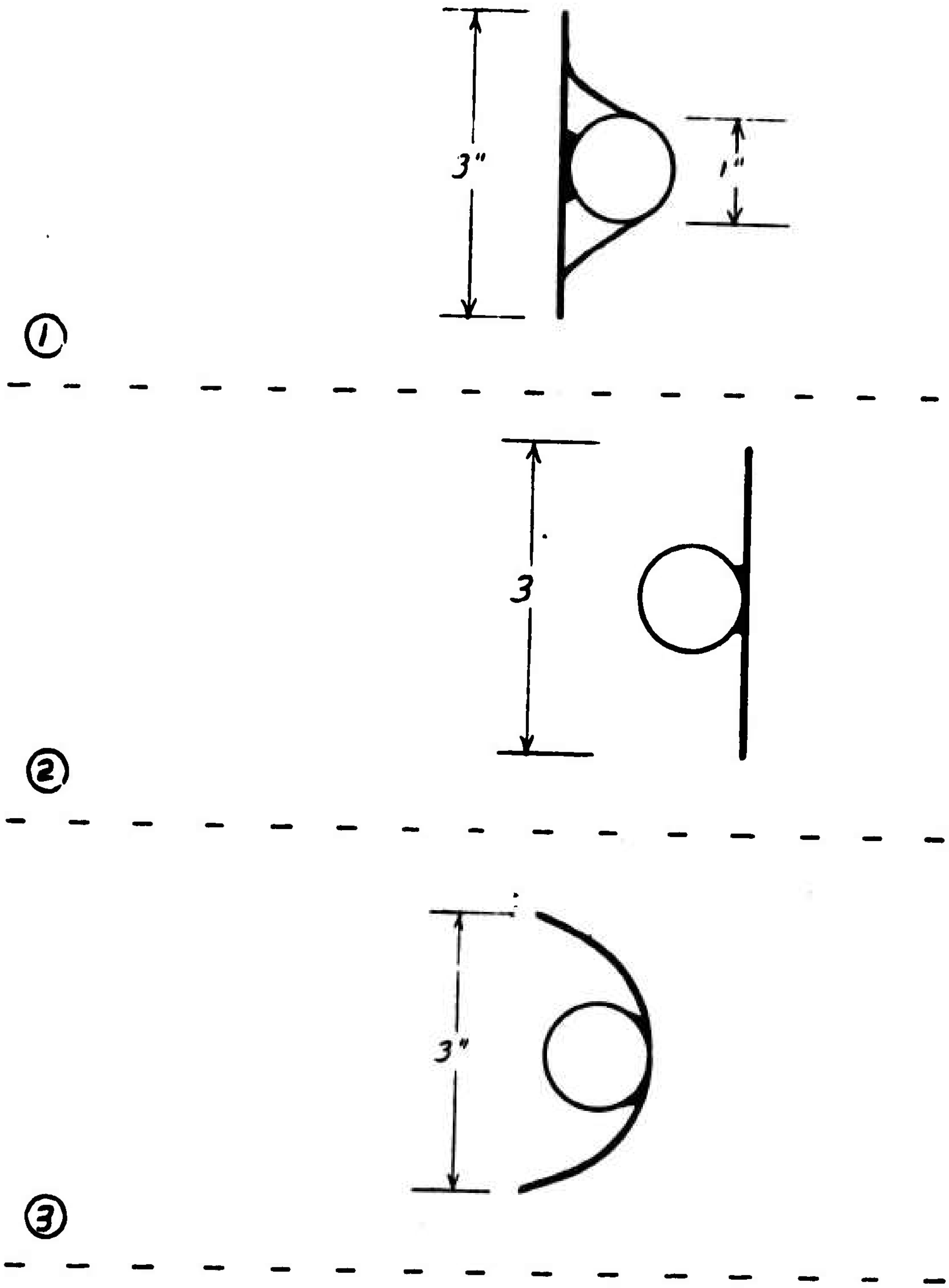


Figure 23 - Piping Target Configurations

If the signal to noise ratio is the limiting factor on resolution, a thermometer with a specified 0.1° temperature resolution will require 10 times the energy at a given temperature on its detector as will a thermometer having a 1° resolution.

If the intended target is smaller than the thermometer's target spot size, an artificial target must be constructed and attached in direct thermal contact with the intended target. We must then consider just how much error we can expect because of imperfect thermal conductivity. Attempts to measure the temperature of a fluid in a pipe by looking at the outer surface of the pipe will be unsuccessful if thermal gradients from the inner to outer surface of the pipe exceed the acceptable measurement tolerance.

High speed electrons transfer heat energy from active atoms in the hotter portions of metals and alloys to less active atoms in colder portions. This mechanism is called conduction. The relative thermal conductivity between two metals at some temperature is in fact nearly proportional to the relative electrical conductivity at that temperature.

Good choices for piping where thermal gradients are to be minimized are copper and iron alloys with a minimum of nickel. Unfortunately piping chosen for applications in salt water environments often have high nickel content to resist corrosion.

The precise value of the thermal gradient through a material is a function of the total heat radiated, conducted, expended by evaporation, and other dissipative effects. If no energy were lost at the outer surface of the pipe, thermal equilibrium would be reached with no thermal gradient in the material.· Otherwise, a thermal gradient will exist and the pipe's outer surface not be the same temperature as the fluid it contains.

In the selection of a target, one must choose a configuration which minimizes heat losses but still satisfies the requirements of the Telatemp 44.

Three possible target configurations for smaller piping are diagrammed in Figure 23. In all cases the temperature measurement desired is that of the fluid in the pipe. The pipe is less than 1½ inch diameter and is metallic. The target is also metallic and the integrity of the thermal contact is equal in all cases.

Arrangement #1 provides a nearly uniformly heated target with an emissivity determined solely by the coating on the target plate. The plate should be sufficiently thick to quarantee proper conduction of heat to its outer edges. Yet it must not be so thick that a large thermal gradient would exist across the plate. A major disadvantage of this target arrangment is that heat must be conducted through the target disk to the emitting surface.

Arrangement #2 sacrifices the uniform geometry of the target area enjoyed in arrangement #1. The improvement is in the thermal conduction to the viewed surface. In addition, heat radiated from the pipe surface near the target will be absorbed by the target. A thinner plate could probably be used than in #1.

Arrangement #3 is a more sophisticated version of arrangement #2. The target is folded around the pipe to further improve the conduction and radiation of heat to the target from the pipe.

The latter two arrangements have an additional advantage in that the target plate is somewhat protected by the pipe itself.

In order that the target temperature represent that of the fluid, heat losses must be minimized. Reduction of radiated heat can be accomplished by retaining a low target emissivity except for those areas which the thermometer views or which radiate to the target area. High emissivity of the target ar[illegible] should be maintained. Conduction losses can be reduced by restric[illegible] ir flow past the target. Restricting air flow also reduces the supp[illegible] [illegible] either warmer air which may cause condensation on the target or colder air which may contribute to evaporation.

A blackbody which is perfectly insulated from its surroundings would make an ideal target. This is not possible. However, the replacement of the flat plate of Figure 23 #1, by a partial cylinder, #3, has distinct advantages. If the thermal conductivity of the material is good enough so that the edging is nearly the same temperature as the target surface, the edges tend to increase the apparent emissivity of the target.

III.C. Accuracy and Resolution

The wide bandwidth of this instrument, 2-15 microns, permits measurement of a wide range of temperatures without scale changing and with a reasonably good signal to noise ratio.

However, this wide bandwidth encompasses a large number of absorption bands of certain gases. Design and calibration of the Telatemp 44 thermometer assumes minimal infrared absorption by the medium between the heat source and the thermometer. Reasonably dry air with normal concentrations of other gases has good transmission properties over a short distance. Over a 0.3 kilometer distance at sea level, air exhibits transmission properties as diagrammed in Figure 24. Strong absorption bands of CO_2 and H_2O reduce transmission at certain wavelengths to practically zero. Concentrations of CH_4-methane, N_2O-nitrous oxide, and CO-carbon monoxide introduce smaller attenuation at many other wavelengths.

These absorption bands-whose shapes are determined by the partial pressures, temperature, and path length-can produce erroneous temperature

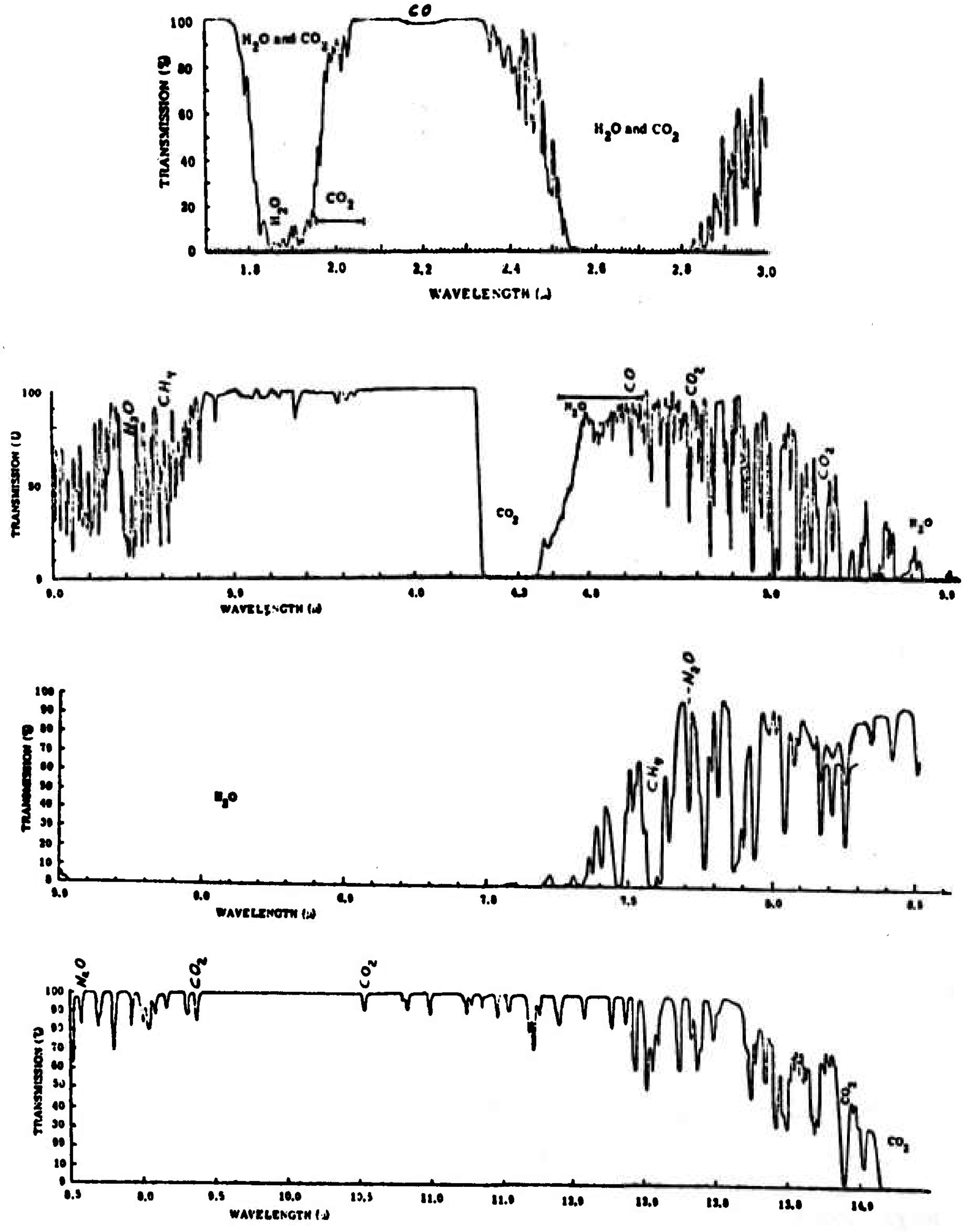


Figure 24 - Optical Transmission of Atmosphere 0.3 Km Path

readings if the spectral transmission is significantly different from that experienced during calibration.

Figure 24 reflects the strong H_2O bands centered at 2.66, 2.73, and 6.27 microns and the strong CO_2 bands centered at 2.69, 2.79, 4.3, 13.9, 14.9, 16.2, and 18.3 microns and a single significant N_2O band centered at 4.5 microns.

Only if the partial pressures of CO_2 and H_2O become abnormally high will these absorption bands become significant over the Telatemp 44's 30 inch path length. Health hazards would exist if CO_2 concentration is abnormally high. Air conditioning would tend to limit H_2O concentration. However, in some shipboard areas the environment is not well controlled, as is often the case in machinery rooms. H_2O concentration or steam, may invalidate readings. Any visible water vapor will produce erroneous readings. At a 10 inch path length, only steam effects readings. At a 45 inch path length a 200°C target appeared 2°C colder when a hot plate with boiling water was placed immediately beneath the optical path. No visible steam was emitted.

Errors at higher target temperatures will generally be greater since the atmospheric absorption in the region of the target will increase. Energy radiated from the target in the gases' absorption bands will heat the gas widening the absorption bands and increasing the absorption coefficient of the band.

The longer wavelength CO_2 bands are most susceptible to changes in absorption coefficients at high target temperatures. The normally weak 9.4 and 10.4 micron bands experience an absorptivity increase of a factor of two for each 30°-40° C rise. No facilities were available to illustrate this increase. Minimal effect is expected and the situation is presented here only to introduce the phenomenon.

Any temperature measurements taken outside are subject to errors resulting from reflected solar energy. The sun, which approximates a 6000K blackbody, is shielded from the target surface by as little as one air mass, at maximum solar ascension. The spectral energy distribution described by Planck's law is modified by the spectral transmission of the atmosphere to give the solar spectrum. This spectrum is reflected back to the infrared thermometer after being attenuated by a factor of 1-E the reflectivity of the target. Strong sunlight has sufficient energy in the 2 to 3 micron range to generate significant errors.

This discussion demonstrates two advantages of band limiting, minimizing atmospheric absorption and minimizing the effect of reflected energy from hot masses and light sources. Band limiting allows one to measure partially transparent or reflective materials. In fact, by selecting an infrared thermometer which senses radiant power in the spectral region where the target material has an emissivity very near 1.00, measurements could be made under ideal conditions; the target could be considered to be a blackbody.

Unfortunately band limiting also limits the versatility of the instrument and in a sense the resolution. Resolution is reduced since the total energy incident on the detector at any given temperature is less than with a wide-band instrument. The fixed instrument noise level then represents a greater percentage of the total temperature signal.

If one needs an IR thermometer to resolve small temperature changes at moderate cost, his solution is limited to wide-band instruments. He must then take every precaution to reduce the effects of atmospheric absorption and reflected energy.

The alternate solution requires a more costly and sophisticated instrument which reduces noise to levels consistent with the required resolution.

The noise effective temperature (NET) of the Telatemp 44 infrared thermometer is specified at less than 1°C. The noise effective power (NEP) from which the NET is derived is defined as the power required from a target to produce a signal to noise ratio of one. The system noise is a combination of detector self noise and thermal radiation from the optics and case. The DC components of this noise can be reasonably well compensated for but the random noise cannot. Noise at the detector output is amplified and to it is added noise from amplifier circuitry due to motion of charge carriers in resistive elements.

Preamplifiers, emissivity compensation circuitry and the detector all contribute to this Johnson noise. Johnson noise is reduced to zero at absolute zero temperature. In a portable device such as the Telatemp 44 no effective cooling scheme is practical. Avoiding large excursions of the case temperature above ambient will reduce errors caused by the AC component of noise. Prolonged viewing of a very hot target can elevate the temperature of the detector, thus increasing the AC component of it's noise level. This phenomenon was noted and recorded in the evaluation tests. In practical applications, no errors in digital reading have been observed which can be attributed to detector heat/noise characteristics. The analog output, however, does suffer from an increased uncertainty in what corresponds to the 0.1 degree digit.

Noise increases due to rising detector temperature during readings can be negligible if readings are taken quickly.

The Telatemp 44 thermometer was designed to measure temperatures over the range from 0° to 1000°F (0° to 600°C) with a specified accuracy of +.5% of full scale. At 1000°F the +.5% is acceptable. However, at 100°F the specified accuracy is ±5°F which is ±5% error in reading.

This error is a combination of gain errors, offset errors and nonlinearity. The major contribution to inaccuracy is nonlinearity.

The conversion of the approximate $W = e\sigma T^4$ relationship to an output which is linearly related to temperature requires generating a $1/T^4$ correction curve. The segmented diode shaping scheme used has an inherent error which is the percentage error at the break points. Investigation of the calibration data shows that errors from one to two percent of the correct reading can occur at lower temperature due to nonlinearity.

The break points must occur at levels determined by the forward conduction voltage of the diodes. The number of break points is limited by the power supply voltage to 12. If the same number of segments were used to compensate for a smaller portion of the T^4 curve, deviation from the best-straight-line, our measure of nonlinearity, could be reduced.

SECTION IV - FIELD USE

The Telatemp 44 infrared thermometer was taken on-board a submarine at Charleston, S.C. for an on-site evaluation. Potential uses of the thermometer were pointed out by the SMMS site team and the usefulness of the thermometer for these measurements was noted. Other observations were made by the site team concerning the convenience of this instrument.

IV.A. SWITCH CONTACTS

Electrical switches which are beginning to fail can often be identified by abnormally high temperatures in the contacts. A high resistance contact dissipates energy at a rate of i^2R where i is the current through the contact and R is the resistance. Contacts exhibiting abnormally high temperatures can be replaced or dressed, or the entire switch can be replaced.

Unfortunately, most contacts are much smaller than the required 1½ inch diameter Telatemp 44 target. Some contacts are not accessible during operation. The switch's case or mounting panel may not be sufficiently heated by poor switch contacts to provide IR indications of an impending failure. Where switch contacts are accessible, a device requiring only a small spot size and would be quite effective.

IV.B. SEA WATER PIPING

Relatively large piping, 4 inches or better, would present a sufficiently large target. Piping material varies, sometimes from inlet to outlet. Copper-nickel piping, one type extensively used on submarines, exhibits different emissivities for different alloys. Some surface treatment would be required to establish a uniform known emissivity. Most sea water pipes are lagged to prevent condensation of water vapor from the warm air onto the cold piping. Lagging would have to be removed.

Presently, fixtures are installed and intrusion devices are used to read temperatures. Most often, for heat exchanger applications, temperature differential between inlet and outlet is the desired information. If there exists a 6-degree temperature differential between the inlet and outlet, and the installed thermometers are specified at ± 1 degree accuracy, a 2 degree or 33 percent error between actual and observed values may be experienced. Digital readings taken by this Telatemp Model 44 are no more precise and would result in equally unacceptable data. The analog output, however, can produce better results due to the better resolution.

IV.C. VENT SUPPLY TANK

This large tank presents a satisfactory target area, but the thick walls may contain a large thermal gradient. Inlet and outlet piping is not sufficiently large to view without adding an auxiliary target.

IV.D. OIL STORAGE BAYS

The three bay main hydraulic oil storage bays form a large enough target, but thick walls may contain large thermal gradients. Piping is too small for viewing and access can be difficult.

IV.E. YARWAY STEAM TRAPS

Inlet and outlet temperature measurements are now used to detect partially open valves or valves which are open when they should be closed or vice-versa. Inlet and outlet piping provides sufficiently large targets for IR thermometry. Precise temperature measurements are not required. In fact, due to the thermal contact between the inlet and outlet piping through the trap case, temperatures recorded are meaningless from a quantitative standpoint.

IV.F. HYDRAULIC OIL CONTROL VALVES

These valves are mounted on a supply manifold. Faulty valves are presently detected by subsystem leak path isolation methods. Faulty valves may be located with the infrared thermometer when they exhibit outlet temperatures which are inconsistent with those of other valves on the manifold. Again, as with the Yarway steam traps, precise temperature measurement is not required.

IV.G. MOTOR WINDINGS

Windings are generally found in three different circumstances:

Case 1: no visual access, no forced air cooling
Case 2: no visual access, forced air cooling
Case 3: visual access

For Case 1 and 2, measurements are presently taken by monitoring the housing at the midpoint of the windings with a thermocouple.

Readings for Case 1 can be taken with the Telatemp 44 much as the thermocouple readings are presently taken. Both thermometry methods suffer an error due to conduction losses from the windings to the outer surface of the case.

Readings for Case 2 could be taken as in Case 1 or by monitoring outlet air temperatures on a target installed in the air flow. Such measurements must be compared to readings taken from good windings, since the thermal contact between the windings and the target is through air.

Readings for Case 3 may be made through a screen. Grid size may be about ½ by ½ inch made from 1/32 to 1/16 inch wire. The larger value of wire thickness corresponds to heavily painted wire screen. These wire sizes produce an IR transmission interference of 10 to 25 percent. The effect of the screen can be minimal if (1) the screen is warm and (2) the screen is as thin as possible. These readings are further complicated by the irregular emissivity presented by the windings and spaces. Readings on accessible windings are now taken with a thermocouple after warm-up and shutdown.

IV.H. OTHER

Other potential applications may be to monitor operating temperatures of the reduction gears, shaft bearings, and pump bearings. Efficiency of air conditioning systems can be monitored. Wetted pipe lagging can be detected. Dry lagging has very good thermal insulating properties, its outer surface is very near room temperature. Wetted lagging may be at nearly the same temperature as the piping.

Two interesting situations occurred while making surface temperature measurements aboard ship. Air from an air conditioning vent striking one side of a heat exchanger pipe caused a 4^{o}F differential between two sides of the pipe. Another problem was noted when the temperature of a surface was read after one of the ship's personnel had been leaning against the surface. The normally cold area was significantly heated by the body heat. Intrusion thermometers if applicable to the situations, are less susceptible to errors caused by external influences.

Negotiating one's way through a submarine and up and down ladders with a handheld Telatemp 44 may prove to be quite a problem. The carrying strap included by the manufacturer of the Telatemp 44 would make the thermometer a free swinging mass subject to sure damage. A chest holster may help.

SECTION V - USE TECHNIQUES

Successful field application of an infrared device to measure surface or fluid temperatures can be achieved if a suitable target exists.

A suitable target must meet three requirements:

(1) It must be large enough to encompass the thermometer's required target spot size.

(2) It must have a known emissivity, preferably 0.90 or higher.

(3) Its surface temperature must represent the temperature measurement of interest.

Requirement (1) is easily met by affixing an auxiliary target if the objective itself is not a suitable target. The target must not alter the temperature of the objective, and it must be in close thermal contact with it to satisfy requirement (3).

If targets meeting these three requirements are used, most proposed submarine applications will be possible with minimal effect on the objective to be measured. Perhaps the most negative consequence will be that areas which have been carefully protected or shielded will have to be exposed to permit the periodic measurement. Protective covering removed from cold pipes will expose them to sweating, and covering removed from hot pipes will present a possible hazard.

Coating the target or the objective's surface with Krylon Ultra Flat Black paint will provide a target with an emissivity of .93 or better. If the target area is protected from oil, water, and dust, the emissivity should remain constant. Where lagging covers a pipe which would otherwise present a usable target surface, one need only remove a plug of lagging somewhat larger than the required spot size and apply sealer to the inside of the generated cavity. A high emissivity paint should be applied to at least the pipe surface.

Unlagged pipes presenting sufficient target area need only be painted with the high emissivity paint. Unlagged pipes smaller than the beam size will require the application of an auxiliary target.

The target area chosen must experience no direct air flow from cooling ducts. It must be easily accessible for taking readings. It must not be exposed to oil spray, dust, or water. Target areas should be clearly marked as such to prevent tampering.

The target, whatever its geometry, must be fixed and its emissivity established. Any thermal gradients which exist at normal operating conditions should be noted. The thermal gradient can be determined by noting the difference in temperature between a thermocouple installed on the outer surface and an intrusion device. This technique, however, is impractical in most submarine applications.

Most often, and experience will indicate when, the thermal gradient will be insignificant and can be ignored. If the thermal gradient is desired where no intrusion device exists, the gradient can be approximated by that existing in a similar arrangement with a comparable fluid temperature, pipe material, and pipe thickness.

Having determined the target differential from the fluid, the thermocouple can be removed, the surface cleaned and the high emissivity paint applied. Allow the target surface temperature to stabilize and then attempt to read its temperature. Adjust the emissivity control until the displayed digital output differs from the fluid temperature by the gradient. Both the experimentally determined gradient and emissivity should be noted and retained by the SMMS team.

Once suitable targets have been installed at all monitor points, the site team member delegated the task of obtaining the temperature information can simply make his rounds with his chart of target emissivities.

Although no requirement for periodic recalibration was determined, on-site calibration should be possible. Then the thermometer could be calibrated on a regular schedule or whenever the instrument is dropped or exposed to dirt or spray which may cloud the front plastic. The calibration source described in the Appendix would be useful for on-site calibration.

RECOMMENDATIONS

Although a useful instrument in its present form, certain modifications are recommended to enhance that usefulness.

1. A reduction in the target spot size to ½ inch (1.27 cm) at a measurement distance of 15 inches (38 cm) is recommended to make target selection easier. Such a reduction would permit measurements in all but very few places without requiring an auxiliary target. Simple surface preparation would be the only requirement. The total energy incident on the detector would be reduced, however. This reduction decreases the signal to noise ratio at the detector output. If the self-noise of the existing detector is too high, a better detector may be required.

2. Better shielding of the detector from off axis radiation is recommended to reduce the effect of external influences. The existance of a fringe area surrounding the nominal 1½ inch spot suggests that direct rays or rays reflected from the inner surface of the case are reaching the detector.

3. A reduction of instrument bandwidth from the original 2 to 15 microns to a range of 8 to 14 microns is recommended to further reduce the influences of external influences. Primary absorption bands of CO_2 and H_2O fall outside this recommended range. Transmissivity of the optical path will become nearly independent of the existence of these compounds. Bandwidth reduction further reduces the energy incident on the detector, compounding the signal to noise ratio noted in recommendation 1. The bandwidth reduction is most easily accomplished by installing filters in front of the optics. Or a new detector could be selected which has a higher gain in the reduced bandwidth range desired.

4. A reduction in temperature operating range is recommended to improve instrument accuracy. With a 0° to 500°F (260°C) range, the 12 segment diode circuit could be adjusted to more ideally compensate for the T^4 factor, improving calibration linearity.

A one-tenth degree digit could easily be obtained by further limiting the range from 0° to 99.9°C. However, a 99.9°C maximum would not permit reading steam pipe temperatures. The improved display resolution would permit readings of differential temperatures to 0.1 degree if total noise levels, linearity, and accuracy were also within the 0.1 degree range.

The Telatemp 44 IR thermometer evaluated in this report has since been modified to incorporate many of these recommendations. The modified bandwidth is 8-14 microns, the modified target spot size is ½ inch (1.27 cm) at 15 inches (38 cm), and the modified temperature range is 0° to 500°F (260°C). The effects of these modifications are presently being investigated.

CONCLUSIONS

The major argument in favor of IR thermometry is that it is noncontact thermometry, thus no heat is removed from the source other than that which is normally radiated. This apparent advantage of IR thermometry becomes exciting where a temperature measurement is required on an objective which does not have a large mass compared to that of a thermocouple. The Telatemp 44 requires such a large target, however, that this advantage of noncontact thermometry disappears.

Physically inaccessible points can be monitored by IR thermometry if a clear "line of sight" exists. Prior to IR thermometry, inaccessible meant many things. Inaccessible meant an environment where operator safety is not assured. It meant a target whose temperature is higher than upper limits of contact devices. It meant rotating targets where contact is not possible. IR thermometry has allowed temperature measurements to be made under conditions previously considered impractical.

An infrared thermometer can measure the temperature of objects whose temperature fluctuates perhaps a hundred times per second. It can provide a spatial average temperature of a material with only one reading. The large target area Telatemp 44 is particularly suited to such an application. Infrared thermometers can quickly make many measurements over a large surface, giving a "picture" of temperature contours.

The Telatemp 44 does realize many of the advantages of infrared thermometry. Although limited to high emissivity target surfaces larger than 2 inches (5 cm) in diameter, surface temperatures can be rapidly measured to within $\pm 3^{o}C$ or $\pm 5^{o}F$. Using calibration correction curves, the accuracy of temperature measurements between $40^{o}C$ and $185^{o}C$ (104-$365^{o}F$) can be improved to $\pm 1.5^{o}C$ or $\pm 2.5^{o}F$. Under ideal conditions, and using the higher resolution analog output, absolute measurements within $\pm 1^{o}C$ or $\pm 1.8^{o}F$ and temperature differential measurements within $\pm 0.5^{o}C$ or $\pm 0.9^{o}F$ may be expected.

An infrared thermometer such as the Telatemp 44, backed up with a local calibration standard like that described in the Appendix, should prove a valuable tool for SMMS site teams.

APPENDIX A

A CALIBRATION STANDARD

A calibration standard having the required temperature range and accuracy, and emissivity range and accuracy, to completely exercise the Telatemp 44 was not obtainable within available funding. After trying and rejecting several of those available, a calibration standard was developed following a suggestion from Dr. Felix Schweizer of the Metrology Engineering Center in Pomona, CA.

The standard consists of a fluid-filled stainless steel beaker heated by a common hot plate. A metal cover over the beaker supports a small stirring motor and an NBS-calibrated liquid-in-glass thermometer. The thermometer bulb and stirring impeller are immersed in the heated fluid. A closed-end metal tube extends into the fluid through the side of the beaker. The inside of this tube is painted with the .93 emissivity paint and the bottom serves as the target for the IR thermometer. Since the target is practically surrounded by painted tube walls, the effective emissivity approaches that of a true blackbody, unity.

Two such calibration standards were constructed. The first used a 5.8 litre beaker as the basic container, with a smaller, flat-bottom beaker as the target tube. The second used an 8 litre beaker with a target tube having a sharply angled bottom to further increase emissivity.

In operation, the large beaker is filled to within about 3/4 inch of the top with either oil or water. Water may be used for 0°C to 100°C calibrations. Oil must be used above 100°C. Synthetic oils are being tested for the baths. Mobil #1, one such oil, has been used from -10°C to +170°C with good results. Low viscosity at low temperatures permits easy stirring. A low rate of evaporation at high temperatures, and a high flash point allow calibrations at high temperatures.

The fluid acts as a constant temperature sink to maintain the walls and ends of the target tube at a fixed temperature. The fluid is stirred continuously to minimize thermal gradients within the bath. The fluid is stirred so vigorously that if unrestrained it would be forced from the large cylinder. With this degree of stirring, a thermocouple immersed in the bath registers less than ½°C difference between the top and bottom at a bath temperature of 150°C.

Figure 25 shows the 8 litre standard assembled. Note the stirring motor, the thermometer, and the black background for the thermometer.

Figure 26 shows the cover assembly fitted with an adapter ring for the 8 litre standard. Note the stirring mechanism and the thermometer hanger.

Figure 25 - 8 Litre Calibration Standard

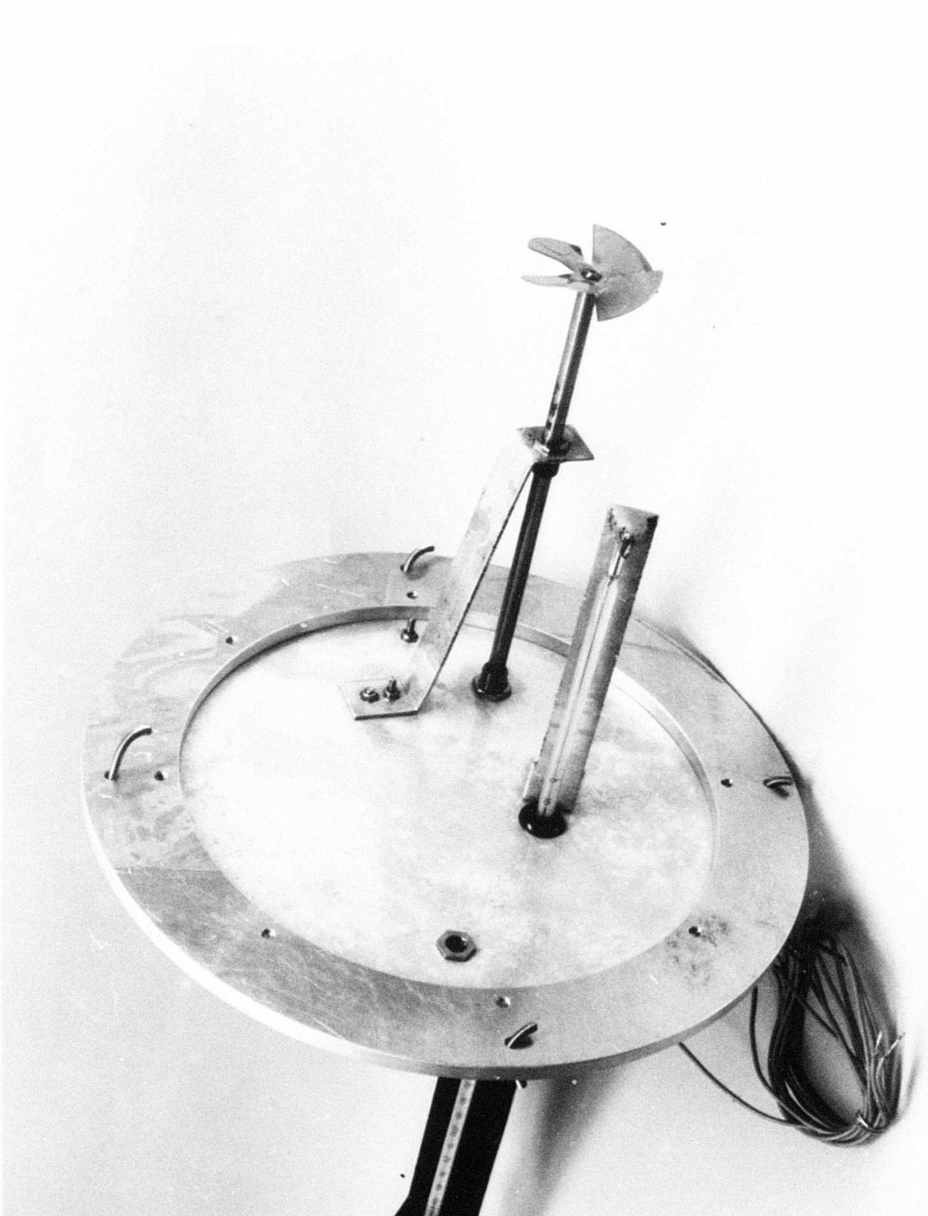


Figure 26 - Cover Assembly

With the fluid level in the bath 3/4 inch from the rim of the large beaker, the glass thermometer is immersed to 76 mm as required for calibration. Expansion and contraction of the fluid in the bath, and the non uniform surface caused by stirring change this immersion level less than 10 mm or about 6°C. This immersion error corresponds to a reading error of:

$$\text{stem correction} = 0.00016n\ (T-t).$$

where

n = number of degrees equivalent to length of immersion error (+ or -)
T = bulb temperature
t = average temperature of the glass at the immersion level

No correction is required since n is small and t is very near the fluid temperature in the enclosed bath.

Unfortunately, with the thermometer immersed to this level, its temperature scale is obscured up to about 30°C. Readings below this temperature are made by lifting the thermometer and reading quickly.

Figures 28 and 29 show the cavity geometry of the two standards. The 5.8L standard has a cylindrical cavity with a flat normal rear surface. The 8L standard has a flat surface angled at 45° so that reflected rays are from the cylinder walls and not from the exterior of the cavity. The inner surface of the cavity is painted with Krylon Ultra Flat Black paint with an emissivity of about .93. The cavity emissivity is, however, much greater.

The method of Gouffé is used to calculate the emissivity of the 5.8L source since the cylinder geometry is covered by Gouffé. Figure 27 shows the dimensions used.

effective total emis. $\varepsilon_o = \varepsilon_o^1\ (1 + k)$

where $\varepsilon_o^1 = \dfrac{\varepsilon}{\varepsilon(1-a/A) + a/A}$

and $k = (1-\varepsilon)(a/A - a/A_o)$

and
a = aperature area
A = area of interior surface
ε = surface emissivity
A_o = the surface of a sphere of the same depth as the cavity in the direction normal to the aperture

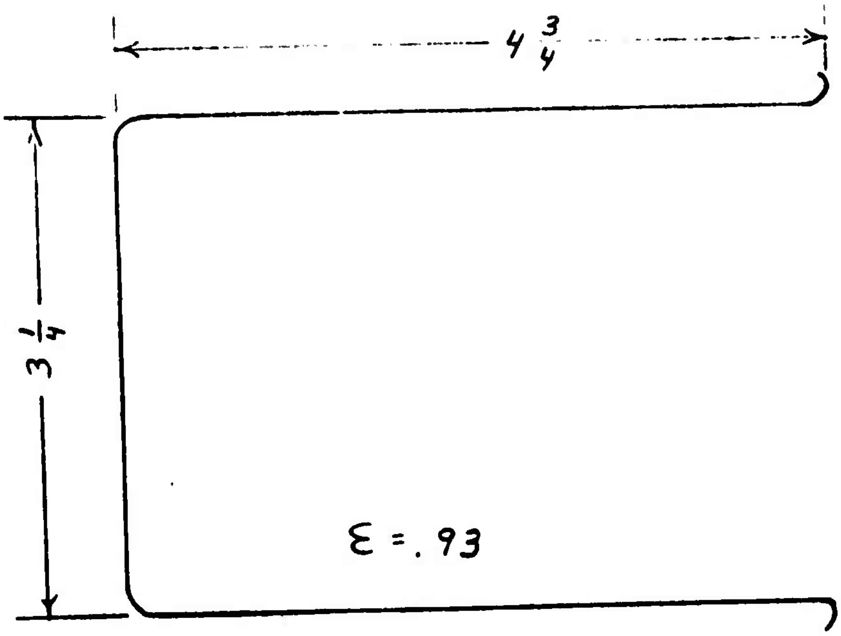


Figure 27 - Cavity of 5.8 Litre Standard

Using this relationship the effective total emissivity, ε_o, of the 5.8L target is found to be 0.991. Emissivity is improved in the 8L source with the sloped-bottom target.

To be certain that the cavity surface is at the temperature of the bath, the bath must be held at a stable temperature long enough to allow the cavity temperature to stabilize. As a rule of thumb, if any drift on the Telatemp 44's analog output is noted, the source is not stabilized and readings are invalid.

Both the cavity and the liquid-in-glass thermometer have a response time. Both must stabilize. Best results are obtained by repeating the sequence of applying a fixed positive increment heat and allowing the bath to fully stabilize before taking a reading.

The 8 litre standard was used extensively to evaluate the Telatemp 44 infrared thermometer. The standard is accurate, relatively inexpensive, and easy to use. The standard is a practical and necessary accessory for field use of infrared thermometers, allowing routine local calibration to ensure thermometer accuracy.

Figure 30 shows the set-up used for calibration sequences performed with the 8 litre standard. Components shown are the standard itself, the hot plate to elevate the temperature of the bath, the power supply to power the stirring motor, the Telatemp 44 mounted on a tripod, and a digital voltmeter to obtain analog readings.

Figure 28 - 5.8 Litre Target Configuration

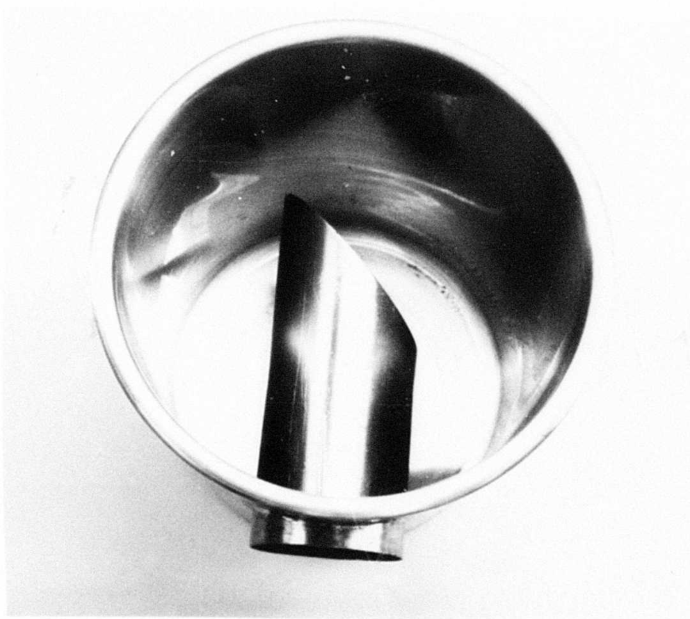


Figure 29 - 8 Litre Target Configuration

Figure 30 - Setup for Telatemp 44 Calibration

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